SSD-TDR-62-14

May 1962

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DEVELOPMENT OF POSITIVE EXPULSION SYSTEMS FOR CRYOGENIC FLUIDS

FINAL REPORT - PHASE II AND III

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BEECH AIRCRAFT CORPORATION
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Beech Engineering Report No. 13511

Contract AF33(616)-6930
Project No. 3084
Task No. 30273

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6593 TEST GROUP (DEV)
ROCKET RESEARCH LABORATORIES
SPACE SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
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FOREWORD

This contract has been monitored by the Rocket Research Laboratories, Space Systems Division, Air Force Systems Command, Edwards, California. This document is based upon the work which was accomplished by Beech Aircraft Corporation, Boulder Division, Boulder, Colorado, under Air Force Contract AF33(616)-6930. Capt. J. Geller of the SSD is the Air Force Project Engineer in charge of the work accomplished under the contract. Technical personnel contributing to the project include:

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This is the final report submitted per Phase II and III of the contract. This report discusses all work accomplished from 15 January 1961 to 20 November 1961. Phase I of the contract has been reported by AFFTC TR 60-70.

ABSTRACT

This report describes work performed under Contract AF33(616)-6930 pertaining to the design and development of systems utilizing bladders to expel cryogenic fluids under zero "g" environment.

During Phase I of the program reported by AFFTC TR 60-70, a material survey and testing effort led to the selection of a Mylar film bladder for the liquid hydrogen expulsion test program. The tests were conducted in a glass dewar in order to observe the bladder during expulsion. A three-ply bladder completed 79 successful liquid hydrogen expulsion cycles.

Phases II and III of the contract will be described in this report. The operation instructions, prototype testing program, and the manufacturing procedures required to develop a prototype unit ~~will~~ be presented.

A 27-gallon, liquid hydrogen expulsion unit was fabricated to test a series of three-ply Mylar bladders. The test program describes the data required and the test setup used to determine the heat transfer rate and the operational characteristics of the prototype system. A summary of problem areas, bladder failures and gas pressure regulator malfunctions has been included together with possible solutions. The report is summarized with a list of recommendations for future expulsion units.

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1.0 PHASE I DEVELOPMENT SUMMARY

This section will briefly summarize the program conducted during Phase I of this contract. A complete report of this phase is extensively described in AFFTC TR 60-70 dated December 1960. The objective of the total program has been to evaluate various expulsion systems for use over a large range of capacities and to develop an efficient, reliable, lightweight expulsion system suitable for positive expulsion of cryogenic fluids during zero "g" environment and which would also provide capabilities for multiple restart of liquid rocket engines. The preliminary design and test formulation of Phase I is outlined under the following eight (8) work sections:

(1) Literature Study
(2) Expulsion Concepts Study
(3) Parametric Design Study
(4) Bladder Material Evaluation
(5) Bladder Development and Fabrication
(6) Testing of Bladders
(7) Design of a 1000 Gallon Tank
(8) Formulation of Test Program for the Phase II Prototype (Breadboard) Tank

The initial phase of the literature survey was directed toward a determination of the "state-of-the-art" in order to avoid duplication of past effort. The results and achievements of similar projects were investigated as permitted by available reports. Thereafter, the scope of the survey was expanded to embrace such fields as materials, fabricators, and techniques.

It became evident that the positive expulsion of non-cryogenic fluids had been well developed by a substantial number of programs. The literature, however, indicated that the art of positive expulsion of cryogenic fluids was in the very initial stages of development and was nonexistent for liquid hydrogen. As a result of the study, the use of a plastic-film bladder was selected from a wide range of concepts initially studied. From this point through the program, primary emphasis was placed upon the development of the bladder principle.

1.1 Bladder Concept

The term "bladder," as generally used in the field of the positive expulsion of a stored liquid, denotes a membrane (often a plastic film) so shaped as to produce a bag. This bag is generally tailored to fit the inside of a rigid container or tank. Some provision must be made to mount and seal this bag within the tank so that the fluid will be contained either within an expanded bladder or outside the bladder if deflated. Positive expulsion is achieved by the introduction of a pressurizing gas on the side of the bladder which is opposite the contained fluid, causing the bladder to deflect and forcing the fluid to flow out by means of a withdrawal line.

The bladder referred to as a "spherical" bladder throughout this report is a fully collapsing bladder. It is tailored to fit, when fully expanded, the inner contour of a spherical tank. It is generally mounted and sealed by a stem assembly at one of its poles as shown in Figure 1.1. The common practice with fully collapsing bladders is to introduce a withdrawal tube through the stem assembly, and this tube is generally extended to within approximately 1/4 inch of the opposite tank wall.

Figure 1.1 shows how the spherical bladder may be applied for both inward and outward expulsion. There is no apparent substantial advantage of the one "direction" of expulsion over the other. Much consideration has been given to the possibility of fluid being trapped in areas isolated from the outlet when outward expulsion is employed. An analysis of this situation shows that such a condition will not develop though the rate of expulsion may be somewhat reduced at times; and subsequent tests with cryogenic fluids with high and low densities, even when working against one (1) gravity, have substantiated this conclusion. It is concluded that both methods of expulsion will generally produce equal stresses upon the bladder even where inertial forces are concerned. It is anticipated that 95 to 98 per cent expulsion can be achieved with either method of expulsion.

The major advantage of the fully collapsing bladder is that it may be introduced into the tank through a very small port. The consequential need for only a small "neck" fitting and cover plate produces a most substantial saving in total tank weight. Even the enlargement of the tank opening to accommodate the pressurant storage cylinder reduces this advantage by only a slight amount. A means for ready removal of the bladder and other interior components, for inspection or replacement purposes, is provided without any penalty in weight.

The fully collapsing bladder is concluded to be the most simple to fabricate. Several types of materials have proven to be promising in cryogenic applications. Fabrication techniques have been developed which may be utilized to fashion bladders successfully. The small opening necessary to accommodate the stem assembly drastically simplifies a critical seal problem.

1.2 Material

During Phase I, manual testing and a mechanical flexing apparatus were used to determine the relative flexibility of bladder material at liquid-nitrogen temperature. If a material was incapable of flexing at 77°K, it certainly would not perform any better at 20°K and was therefore eliminated. All manual testing in liquid nitrogen was conducted in the same manner. Samples were submerged in the liquid until completely cooled down. Any sample which exhibited the characteristics of brittleness was rejected. Strip samples of the materials which passed the preliminary flexibility test were pulled back and forth across a "mandrel" submerged in liquid nitrogen. Such samples were first tested unfolded and then were folded once longitudinally. Better materials were capable of a second fold before failure and, in some instances, were even twisted. Every possible effort was made to duplicate test conditions.

Though little hope was extended that many of the samples would qualify all available samples received this preliminary testing. Over seventy-five (75) samples were so tested. In some cases, samples were of like materials, but products of different producers; some materials were tested in several gauges to observe any trends produced by material gauge.

The materials and composites or variations thereof which qualified are as follows:

Mylar

Type A, 1/2 mil and 1 mil gauges performed the best. Mylar with vacuum deposited aluminum performed equally well; samples with seams of Schjeldahl GT 300 tapes produced good results; laminates by Schjeldahl which performed comparatively well were of 1/4 mil and 1/2 mil Mylar laminated to one or both sides of .8 oz. and 1.85 oz. nylon and 1.85 oz. Dacron; a 1/4 mil Mylar to 1/16 inch deer skin laminate (laminated by Schjeldahl) exhibited excellent performance and remained completely flexible; 1/4 mil Mylar laminated direct to 9 oz. Dacron felt (laminated by Schjeldahl) performed very well; and a Shamban laminate of 21 oz. Teflon felt to both sides of various gauges of Mylar became comparatively stiff, though no film failure was indicated.

Teflon-FEP

1/2 mil and 1 mil gauges produced the best performance; 2 mil gauges indicated some rigidity. A shamban laminate of 21 oz. Teflon felt to both sides of 5 mil Teflon-FEP became comparatively stiff, but there was no indication of film failure.

Trithene

Type A (unplasticized) 2 mil gauge showed slight rigidity but withstood considerable manipulation in liquid nitrogen.

Kel-F

Grades 270 and 300, unplasticized -- by virtue of qualification of Type A Trithene.

Films rated as marginal in the qualification tests were Teslar (a polyvinyl fluoride film), Scotchpak (a polyester), and several developmental films. In general, these films had less to offer in the way of other established requisites than the previously mentioned qualified films and were subsequently rejected.

Among films which failed to qualify in this test and were therefore eliminated were Type B Trithene, plasticized Kel-F, various coated fabrics, several experimental films, and a variety of acetates, vinyls, polyvinyls, polyethylenes and nylons. Note following table for sample size and manufacturers.

LIST OF FILMS WHICH FAILED TO QUALIFY

Description of Film	Manufacturer	Size of Test Sample
Polyethylene	E. I. du Pont de Nemours, Inc.	2" x 36" x .001
Cellulose Acetate	Eastman Kodak Company	2" x 36" x .0005
Cellulose Acetate Butyrate	Eastman Kodak Company	2" x 36" x .001
Polyvinyl Fluoride	Union Carbide Corporation	2" x 36" x .001
Vinyl Chloride	Cadillac Plastic and Chemical Co.	2" x 36" x .0015
Polyester Film	Cadillac Plastic and Chemical Co.	2" x 36" x .002
Nylon Film	Allied Chemical Corporation	2" x 36" x .002

A sample of 1/2 mil aluminum foil was also subjected to manual testing in liquid nitrogen; though it showed remarkable ductility, wrinkling produced numerous pin holes. It was concluded that metallic foils could not be employed for nonpermeable membranes which must flex and wrinkle at cryogenic temperatures and that they have little, if anything, to offer when thermally bonded to thermoplastic films.

1.3 Bladder Fabrication

The results of the surveys, research, and testing by Beech indicated that the most promising and satisfactory positive expulsion system would use a spherical bladder constructed of three separate 1/2 mil Mylar membranes free to act independently of each other. The details of fabrication of the bladders tested are described in the following paragraphs. The G. T. Schjeldahl Company, Northfield, Minnesota, was the supplier of several preliminary test bladders and of the final bladders for the prototype positive expulsion units described in Section 4.0.

Table 1.2 lists the various types of bladders tested, giving the type of materials and construction for each type of bladder. Figure 1.3 is a photograph of the various bladders mounted on the stem assembly.

The lack of a process for ready forming to contour required that Mylar bladders be fabricated in a series of segments known as "gores" by the industry. These gores may have a variety of shapes, but are generally of "orange peel" configuration with each gore extending from one to the other polar area in the smaller spheres. In the larger spheres, each spherical segment could be composed of two or more pieces. A polar cap is generally employed to eliminate the intersection of numerous seams. A gored bladder does not present a true spherical surface, but rather a series of chords. However, only a slight internal pressure will produce an apparently spherical surface with only a minimum of resultant material elongation. The I.D. of the test dewar is 11.36 inches. The bladders were specified to have an O.D. of 11.50 $\pm$ .13 inches and a minimum of 12 gores so that the maximum material elongation due to pressurizing the bladder in the test dewar (from 12 equal cords to the circumference of the dewar) would be 1.08 per cent, which is well within material elongation limits.

Adhesive-coated tapes are generally employed to produce the necessary seams required to combine the gores into a Mylar or Mylar laminate bladder. Although either butted or lap seams may be used, the butted seam results in less material buildup and less stiffening at the seams. Some developmental activity is being directed toward the perfection of seaming methods which would eliminate adhesive-coated tapes, but the use of high-performance tape such as Schjeldahl's GT 300 does not appear objectionable. New fabrication methods show promise of a one-piece Mylar bladder.

The use of a stem similar to that employed in an automobile inner tube presented the most simple method of achieving both functions of mounting and sealing. The fact that some expulsion systems require a withdrawal tube extending to the bottom of the bladder offers no problem in that the tube may be introduced through the hole in the stem at any time after the stem has been sealed into the bladder.

1.4 Test Objectives

The test objective was to determine which of the 11 bladders procured would produce the best performance in actual expulsion cycles. These expulsion cycles were conducted with liquid hydrogen except one test with liquid nitrogen to simulate the condition presented by the much higher density of LOX. Expulsion was tested in both manners: Inward and Outward. It was decided that, if failure had not been experienced, the testing of a particular bladder would generally be discontinued when a feasibility qualification level of 10 complete cycles had been attained. The premise was that substantial cyclic life might be anticipated for any bladder successfully withstanding the initial 10 cycles. Section 5.0, Conclusions and Recommendations, discusses this premise with regard to reliability.

It is concluded that laminates of Mylar to various base materials cannot meet the requirements for the expulsion of liquid hydrogen. The failure of such laminates at -423°F is considered to be the result of any or all of several factors: excessive rigidity of the base material; severe stresses in the Mylar which are induced by the folding of the base material; or stiffening of the adhesive bonding of the plys which tends to cut the Mylar. Variations of gauge of the plastic film offer no solutions. The 1/4 mil Mylar in the laminates did not possess the necessary flexibility, while the 1/2 mil Mylar in similar expulsion applications did not exhibit the required tensile strength.

The spherical bladder tests indicated that all bladder design objectives were fulfilled. None of the bladder failures can be construed to indicate a design failure in any manner other than in selection of materials. The bladder stem assembly fully eliminated any bladder mounting and sealing problems.

It is considered that the spherical configuration and internal finish of the test vessel contributed substantially to the performance of the successful bladders. Special attention is warranted for future designs to obtain good finishes.

1.5 Test Apparatus

The major portion of the test apparatus was located in a fully equipped test house separated from the control "bunker" by a 12-inch thick blast wall. The entire system was remotely controlled from the bunker since liquid hydrogen was used as the test fluid in the glass dewar. Complete control of the system was possible to permit the filling and expelling of the fluid for either the inward or outward expulsion methods. Figure 1.4 shows the Bladder Test System Schematic.

FIGURE

FULLY COLLAPSING BLADDER CONCEPT

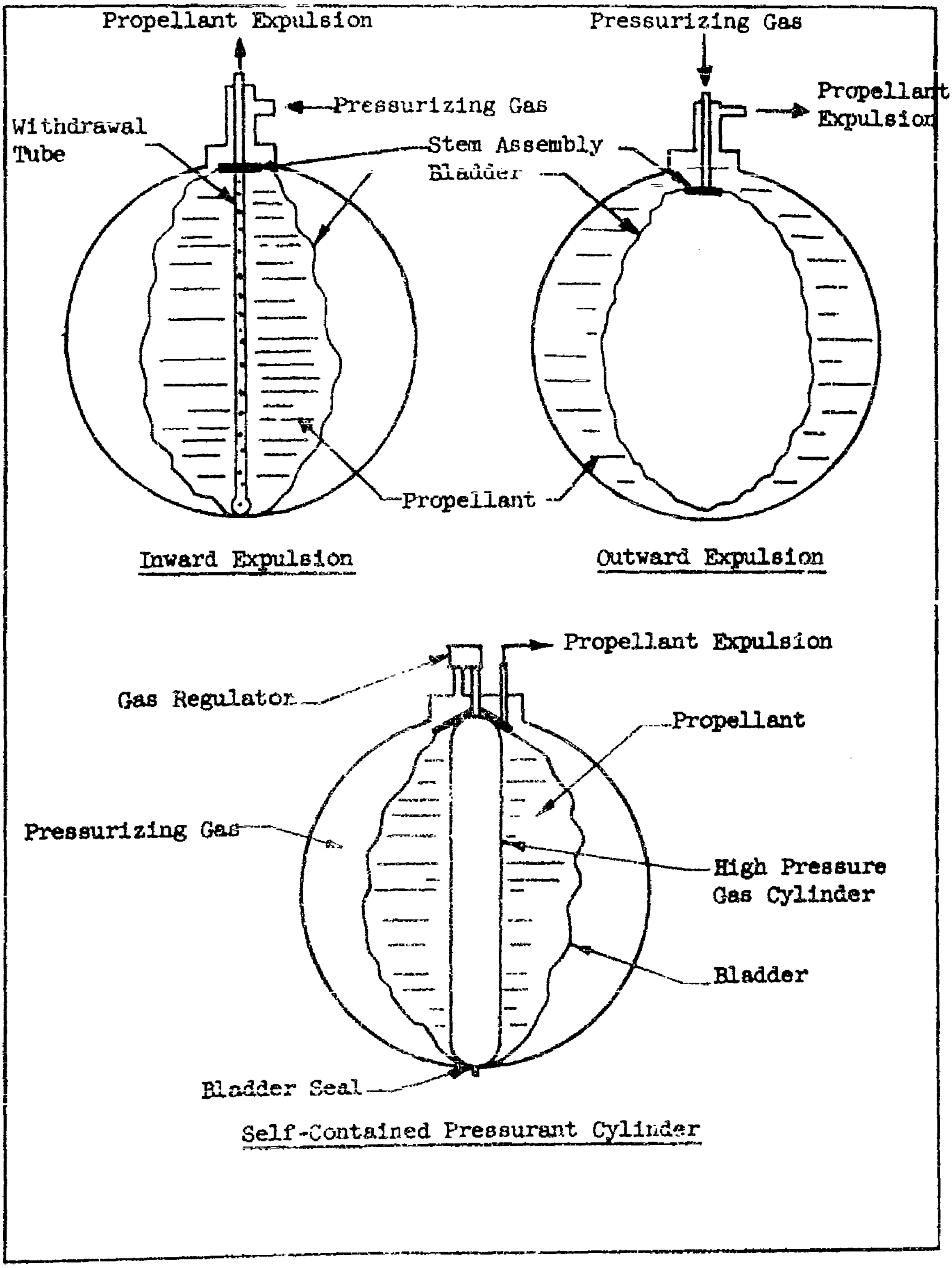


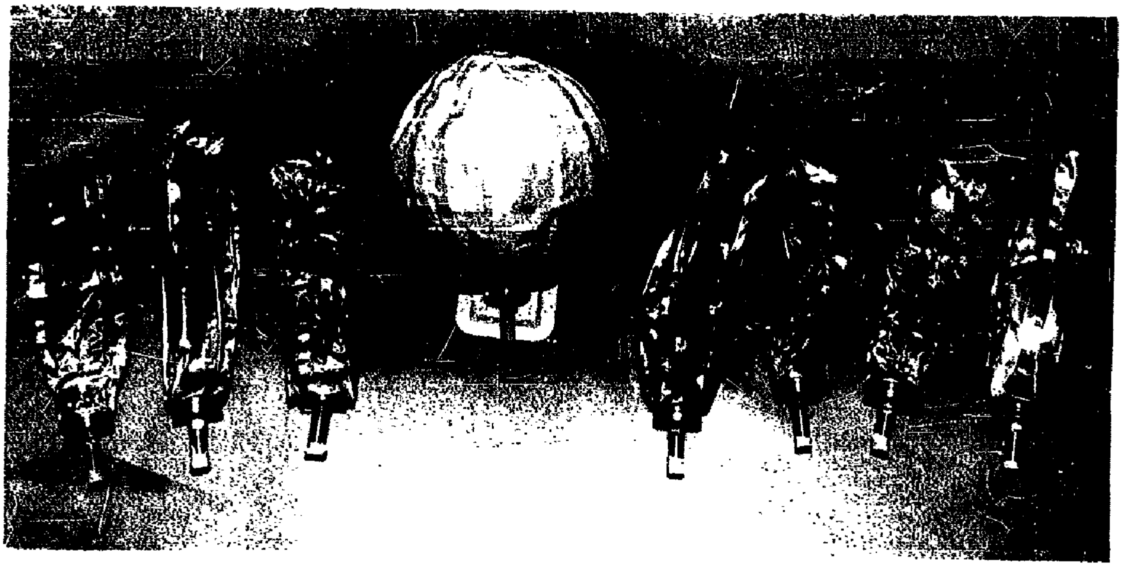
Table [illegible]

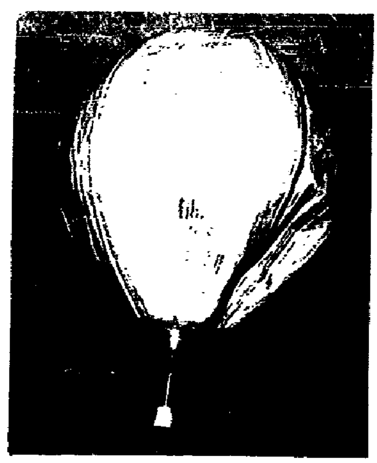
Material and Construction for Test Bladders

Bladder Dash No.	Thickness (mils) and Material			Construction		
	Ply A (Outer ply)	Ply B (Intermediate ply)	Ply C (Inner ply)	Ply(s) to be composed of gores	Plys Unbonded	Plys Bonded
1	1/2 Mylar	1/2 Mylar	1/2 Mylar	X	X	
9	1/4 Mylar	1.85 oz. Nylon	1/2 Mylar	X		X
11	1/4 Mylar	1.85 oz. Dacron	1/4 Mylar	X		X
15	Laminate of 1.85 oz. Nylon to 1/2 Mylar	Laminate of 1/2 Mylar to 1.85 oz. Nylon	Omitted	X	X	
31	1/2 Mylar	1/4 Mylar	1/4 Mylar	X	X	
33	1/2 Mylar	1/16" Deer Skin	Omitted	X		X
	NOTE: All Mylar to be Type A					

FIGURE 1.3

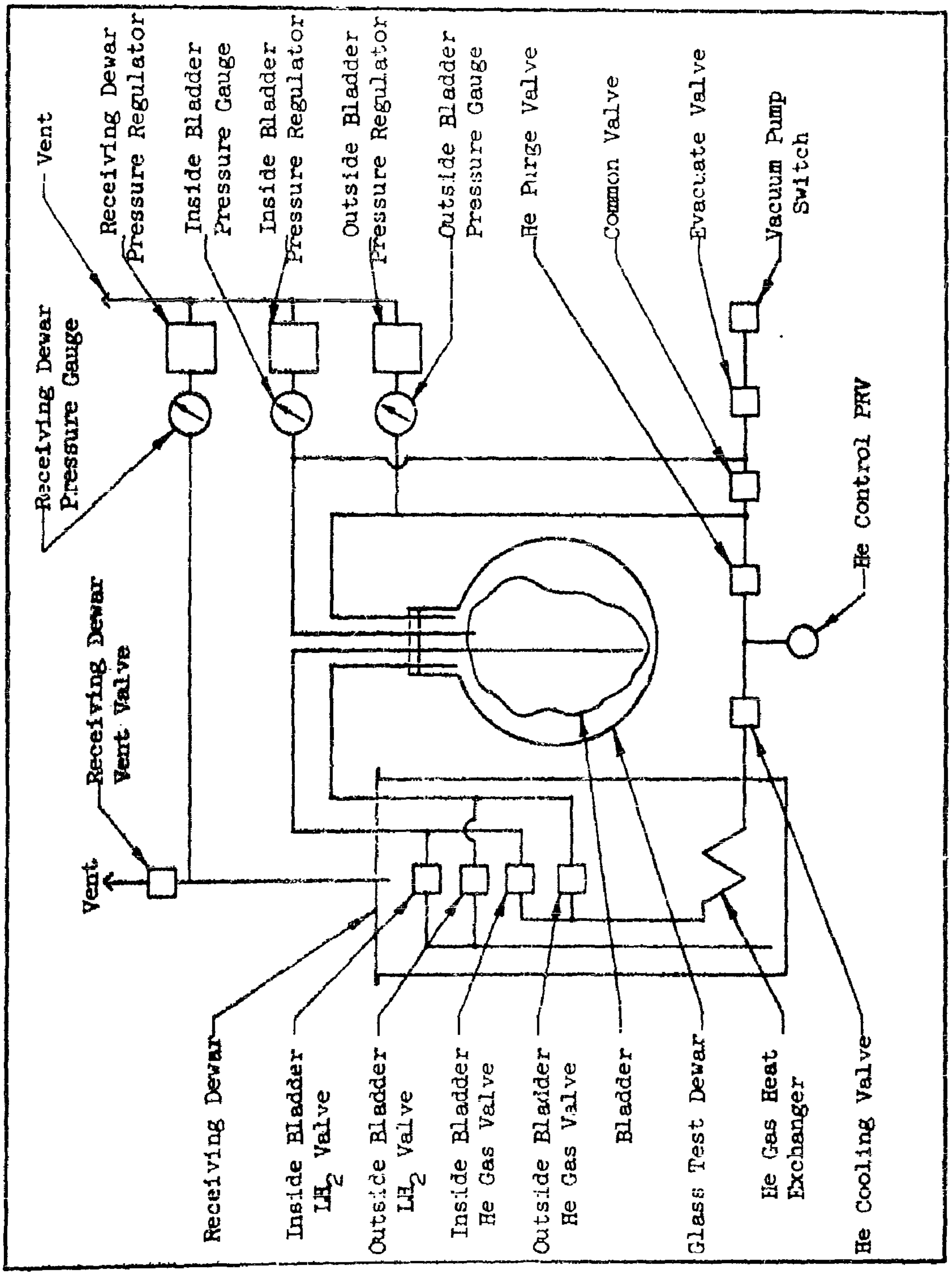
11-1/2" O.D. SPHERICAL TEST BLADDERS





1.4

BLADDER TEST SYSTEM SCHEMATIC



2.0 PHASE II, DEVELOPMENT PROGRAM

This section of the report will describe the positive expulsion system, the operating instructions, and any special precautions to be exercised during a test operation.

2.1 General Description

2.1.1 Purpose

The unit described by this technical manual is a prototype model of a tank system designed to store and expel cryogenic fluids in a zero gravity environment. The principle of positively expelling liquids from a bladder is to be tested and analyzed with this experimental unit.

The prototype model is the result of an analytical study of tankage problem, survey, and selection of material and detail design of system and components.

The ultimate purpose is to develop an efficient, reliable, lightweight tank system for use by flight vehicles in a condition of zero gravity.

2.1.2 Description of Expulsion System

The positive expulsion system consists of a storage dewar, expulsion bladder, helium pressurization system, and the required valves, regulators, and gauges to adequately control the fill, storage and expulsion of the fluid.

2.1.2.1 Dewar

The dewar consists of an inner and outer tank shell separated by a vacuum space and filled with insulating pearlite powder. The inner and outer tanks are bolted together at the top by means of mounting flanges separated by insulating spacers. The dewar maintains the liquid hydrogen as a liquid.

The outer shell of the dewar contains three tie-down connections for cable supports during flight or transportation. These connections are 5/16-24 NF threaded holes located 120° to each other in the neck region of the outer tank.

2.1.2.2 Vacuum Capsule

The vacuum capsule is a closed cylinder attached and sealed to the outer tank mounting flange (Ref. Figure 2.5). The vacuum existing in the dewar also exists in the capsule. The capsule encloses the two-stage regulator (32) and the plumbing lines which connect the regulator and tank to external components.

2.1.2.3 Expulsion Bladder

The laminated mylar bladder is attached to a mounting flange and assembled to the dewar inner tank mounting flange (Ref. Figure 2.6). It is a separate assembly and may be installed when the helium bottle assembly is separated from the dewar. The bladder holds the liquid hydrogen internally and is pressurized externally by helium gas in order to expell the liquid.

2.1.2.4 Helium Pressurization System

The entire system is controlled and operated by helium gas which is stored in a bottle at 2,100 psi located inside the bladder at liquid hydrogen temperature. The gas is used to pressurize the outside of the bladder to expell the liquid hydrogen inside the bladder. Three dome-loaded regulators and two hand-loaded regulators are used in conjunction with valves to control and regulate the system.

2.1.2.5 Instrument and Control Panel (Figure 2.1)

The system is completely controlled from the control panel which contains the pressure gages, hand regulators, selector valves and the helium fill connection. The panel is supported from the vacuum capsule and in turn supports other components.

The panel is divided into an upper half which contains the necessary instruments and controls and the lower half containing the fill and purge valves, connectors and switches. The upper half is completely removable and may be remotely located by extending the lines.

The instruments are 4 pressure gauges mounted at the top of the panel. Gauge (18) is a duplex gauge containing two needles on a scale graduated from -30" Hg to +60 psi. The black needle records the pressure in the bladder (LH_2 chamber) and the red needle shows the pressure outside the bladder (helium pressure chamber).

Gauge (16) indicates the pressure in the high pressure helium storage bottle. It is marked from 0 to 3,000 psi.

Gauge (17) is the pressure of the gas as set by the hand-loaded regulator (14) to pressurize the outside of the bladder. This pressure will be 1 to 2 pounds higher than the needle on gauge (18) which also records the helium chamber pressures. The difference is caused by the drop through the regulator (32). Gauge (15) is a standard 3-15 psi receiver gauge and is used to indicate pressure to the LH_2 valve (33) as set by the 0 to 15 psig hand-loaded regulator (13). It is graduated from 0 to 100 and is related directly to the per cent of opening of valve (33). When the pressure reads 100, the valve is closed.

2.1.2.6 Liquid Hydrogen Transfer Valve (33)

The transfer of liquid hydrogen is controlled by a dome-loaded valve (33) located in series with a filter (35) in the transfer line. The LH_2 valve opening is determined by the 3-15 psi control pressure set by hand regulator (13) and read on gauge (15). The 3 to 15 psi set pressure pilot controls a 60 psi external nitrogen source which is the supply pressure to the valve dome. The piston type valve positioner is actuated by the 60 psi nitrogen supply pressure.

2.1.2.7 Purge System

The purge system includes valves (5), (6), and (7) in conjunction with valve (4). Valve (5) controls the vacuum, valve (7) the helium purge, and valve (6) is a common purge valve to permit vacuum or pressure to be exerted on both sides of the bladder. Valve (4) is placed in "purge" position to equalize pressure in regulator (32) during a purge. See Section 2.4 and 4.2 for purge procedures and principles.

2.1.2.8 Valves (3) and (4)

Valve (3) is a two-position valve whose primary function is to permit the LH_2 chamber pressure to be vented in an emergency. Valve (3) is normally in operation position; but, when placed in "LH_2 Emergency Vent" position, the pressure on the control port of relief regulator (30) is vented, thus opening the relief regulator so that the LH_2 chamber is vented.

Valve (4) is a 3-position valve to accommodate three system operations: purge, operation, and standby.

2.1.2.9 Electric System (Figure 2.7)

Electrical power is required for only two components. A 115 volts AC, 400 cycle receptacle (46) is provided for the power required by the equilibration fan. The fan is located inside the bladder and attached to the bottom of the helium bottle and is controlled by switch (43) located on the panel. The purpose of the fan is to maintain a circulation of liquid in the bladder so that temperature gradients will be be prevented. Maintaining the liquid hydrogen in motion should tend to eliminate hot spots and prevent local vaporization of the liquid. The fan should be in operation wherever there is LH_2 in the bladder.

The second electric receptacle (47) is to provide 115 volt AC, 60 cycle for use by the liquid level sensor and control system. This current is transformed and rectified within the four gang electric box (39) to provide the necessary current for use by the sensor and electric components.

2.2 Initial Preparation for Use

2.2.1 Assembly Instructions

Figure 4 and Figure 5 show the installation and assembly of the dewar, panel, vacuum capsule, helium bottle and bladder.

The positive expulsion system consists of three major subassemblies: (1) the dewar assembly consisting of the inner and outer tank and mounting neck, (2) the bladder and mounting neck, and (3) the vacuum capsule, plumbing system and panel assembly.

The following steps should be followed in the final assembly of the unit:

1. The inner and outer dewar tanks have been previously bolted together with bolts and spacers and the vacuum space filled with pearlite powder covered with a fiberglass filter.

2. Place seal on mounting flange and drop bladder, assembled to mounting flange, into tank being careful not to cut the fragile bladder. Bladder mount will fit over studs secured in inner tank mount.

3. Place seal on bladder mount and seal on outer tank flange. Lower entire plumbing system and vacuum capsule so that helium bottle will go into bladder and mounting plate will fit over studs projecting through the bladder mount flange.

4. Install nuts on all studs using 12 ft. pounds of torque. Install bolts through vacuum capsule outer flange and outer tank neck flange.

5. Connect tubes and wires within vacuum shell.

6. Place seal on upper vacuum capsule flange and install cover with bolts.

The unit is now assembled ready for installation into a test setup.

2.2.2 Installation

The entire system should be inspected for visible damage, loose parts, and tight connections. The system should be internally "LOX clean." Externally, it should be free of any loose dirt, grease, oil, etc.

The system should be installed in a well-ventilated place, with the necessary safety precautions observed with regard to power supplies and auxiliary equipment for performing a hydrogen test.

2.2.2.1 Connection of External Plumbing

Figure 2.1 is a panel and plumbing schematic. The following connections must be made to the system.

1. Nitrogen gas 60 psi
2. Helium gas 2,100 psi
3. Helium purge gas 0-60 psi
4. Vacuum connection
5. Liquid hydrogen 0-20 psi
6. Vent for H_2 and He
7. 115 V - 60 cycle
   115 V - 400 cycle

The 60 psi N_2 gas is required to supply the LH_2 Pneumatic Control Valve with operating pressure. This connection is made directly to the valve using a 1/4" male pipe fitting.

The helium bottle located within the tank requires 2,100 psi of helium gas to provide sufficient pressure and volume to operate the system for the required length of time. The helium fill connector (20) is located on the control panel.

The system also requires a helium source of 0-60 psi for use in purging the lines in preparation for a run. This connection is made on the rear of the control panel directly into valve (7) using a 1/2" tube nut connection.

Purging the system requires a vacuum source and 1/2" O.D. tube nut connection to valve (5) which is located on the rear of the control panel.

Liquid hydrogen is transferred to and from the bladder in the tank from an extended storage dewar through a filter (35) and control valve (33). A 1/2" O.D. tube nut connection is required to match the fitting provided on the filter.

The vent connection is common to both the helium and hydrogen system. Since it is possible to have liquid hydrogen expelled through the vent as well as hydrogen gas, it is necessary to run the vent to a safe area. A 3/4" O.D. tube and connector is made at the check valve (34).

Electrical power connections are made on the electrical box (40).

Input voltages are:

(a) 115 VAC, 115 cycle single-phase for the liquid level sensor and circuit
(b) 115 VAC, 400 cycle single-phase for the equilibration fan

2.2.3 Cleaning

The interior of the tank and plumbing system in contact with helium or hydrogen should be LOX clean according to Beech Specification B.S. 8505A.

2.2.4 Purging

The system must be purged before filling with hydrogen. The vacuum-helium fill technique is used to purge the lines and tank.

The vacuum source and helium pressure source are attached to their respective valves (5) and (7) on the back of the control panel.

CAUTION (1) Prior to "pulling" a vacuum or filling system with helium purge gas, it is essential to OPEN common purge valve (6). If this valve is not open, the differential pressure across the bladder will rupture the bladder.

CAUTION (2) Prior to "pulling" a vacuum on the system, it is necessary to turn valve (4) to "purge" position. Failure to have this valve in this position will cause regulator (32) to permit a vacuum into the 2,100 psi helium line, causing damage to gauge (16).

1. Open common purge valve (6).
2. Turn valve (4) to "purge" position.
3. Open valve (5) and obtain a vacuum of 10 mm of Hg or better in system.
4. Close valve (5) and open valve (7), thereby breaking the vacuum with helium gas under pressure of 0-60 psi.
5. It may be advisable to disconnect the vacuum purge line from the vacuum source so that an emergency vent could be accomplished (see Section 3.5.1 "Overpressurization of Dewar").

The vacuum-fill purge cycle should be accomplished several times to assure the elimination of air which might freeze out when the liquid hydrogen was added. After the last helium fill, turn valve (4) to "ready" position. Following the purging process, the tank and system are ready for filling with liquid hydrogen.

2.3 Operation Instructions

2.3.1 Fill

2.3.1.1 Helium Bottle

Fill the helium bottle (44) with 2,100 psi of He gas through the He fill connector (20). Before opening He fill valve (2), be certain He regulator (13) and (14) are closed and valve (4) is in "standby" position. The pressure in the helium bottle (44) is read on gauge (16). After bottle pressure reaches 2,100 psi, close He fill valve (2). The helium bottle must be "topped off" after the LH_2 fill when it has stabilized at LH_2 temperature.

2.3.1.2 LH_2 Valve, N_2 Control Pressure

Prior to filling the bladder with liquid hydrogen, the LH_2 control valve (33) must have the N_2 supply pressure and control pressure applied to the valve for operation.

The following steps should be followed to fill the bladder with LH_2:

1. Expulsion gas regulator (14) should be set at 0 psi as indicated by gauge (17).

2. The auto vent liquid level switch (41) should be turned to "on" thus activating the electric "auto-fill valve vent" (28) to the vent position, allowing the bladder to free vent to atmosphere through regulator (30).

3. Upon the LH_2 valve (33) by using the hand regulator (13) and permit liquid hydrogen to be transferred from the external storage dewar through filter (35) into the bladder. The rate of fill will be determined by the gas boil-off rate and cool-down time required by the dewar.

4. When the bladder is approximately 1/4 full, turn on the equilibration fan by switch (43).

5. When the liquid hydrogen fills the bladder and contacts the liquid level sensor (37), the liquid level light turns on and indicates a full tank. Simultaneously, the electric valve (28) is returned to normal position to permit regulator (30) to control tank pressure. At this time, the LH_2 control valve (33) should be closed by regulator (13) and the liquid level switch (41) turned off.

NOTE: It is essential that this switch (41) be in the "off" position at all times except when filling or topping off the tank. The "off" position permits the full bladder relief regulator (30) to properly control the pressure within the bladder during standby and operation. In the "on" position, the tank will free vent when the liquid is below the liquid level sensor (37).

CAUTION: The chamber pressure gauge (18), which shows the pressure on each side of the bladder, should be observed regularly during fill and expulsion. The pressure on the outside of the bladder (helium-pressure chamber) and the pressure on the inside of the bladder (LH_2 chamber pressure) should never differ from each other by more than 3 to 5 psi. A difference in pressure indicates the differential pressure across the bladder and could cause rupture of the bladder. See emergency vent Section 3.5 for procedure to prevent or eliminate this pressure difference. This difference in chamber pressure should only occur when the bladder is fully expanded against the walls of the tank or entirely empty collapsed about the helium bottle. See Section 4.0 for complete understanding of inter-relationship of regulators and valve system.

6. After the tank has stabilized at the LH_2 temperature, the He bottle should be topped off to 2100 psi pressure.

2.3.2 Standby

A standby condition is obtained, after the bladder is filled with LH_2, by keeping LH_2 valve (33) closed, expulsion gas regulator (14) closed or at 0 psi, valve (3) in "operation" and valve (4) in standby.

2.3.3 Preparation for Run

After the system has been in standby condition, it is necessary to "top off" the LH_2 in the bladder before making an expulsion run. Topping the tank follows the identical procedure of the original bladder fill as follows:

1. Turn the auto vent liquid level switch (41) to "on" position.
2. Check regulator (14) to be certain it is in "off" position.
3. Open LH_2 valve (33) and permit LH_2 from the storage dewar to be transferred into the bladder.
4. When the liquid level light (42) comes on, shut off valve (33) and turn off liquid level switch (41).

The system is now ready for an expulsion run which is accomplished as follows:

2.3.4 Expulsion Run

1. Turn valve (4) to "operation" position.
2. Leave valve (31) in "operation" position.
3. Turn expulsion gas regulator (14) to desired pressure (0-60 psi).
4. Turn LH_2 valve control pressure regulator (13) to open LH_2 valve (33) the desired amount to expel LH_2 from the bladder back to the storage dewar.

   NOTE: Regulator (14) must be set at a pressure in excess of the LH_2 storage dewar pressure in order to transfer back to the dewar.

   CAUTION: As the bladder nears complete expulsion, observe gauge 18 to avoid excess differential pressures across the bladder. The helium gas pressure chamber may show 3 to 5 psi above the LH_2 chamber pressure but should not exceed this amount.

5. The bladder is empty when gauge (18) indicates a differential pressure between the chambers. At this time, the LH_2 valve (33) should be closed and regulator (14) reduced to 0 psi pressure.

6. Turn equilibration fan (45) off by switch (43).

7. Valve (4) should be turned to "standby."

2.3.5 Emergency Vent

There are three conditions which may require emergency action:

(1) Overpressurization of the dewar
(2) Overpressurization of LH_2 chamber
(3) Overpressurization of helium pressure chamber

2.3.5.1 Overpressurization of Dewar

The pressure in the dewar is dependent upon the helium pressure which is determined by the hand-loaded regulators (14) and boil-off gas pressure of the LH_2. However, if the regulators (29), (30), and (32) are functioning properly, the total pressure in dewar should be controlled by the pressure set by regulator (14). An emergency could only occur if regulator (29), (30), (32), or (14) malfunctioned, permitting total dewar pressure in excess of tank structural limits -- 115 psi. If pressure gauge (18) indicates that both He and LH_2 chamber pressures are high but equal, it is impossible to tell which chamber is causing the high pressure. Since the bladder is a free floating diaphragm between the two pressure chambers, the pressure on both sides of the bladder is equal, excpet at the end of the full or expulsion cycle.

Emergency action to protect the tank and personnel requires one of the two following plans to reduce the pressure.

Plan No. 1 (Assuming the High Pressure is Caused by the LH_2)

1. If the storage dewar is at a lower pressure than the positive expulsion tank, open LH_2 control valve (33) and permit the liquid hydrogen and pressure to be transferred back to the storage dewar.

2. If step No. 1 is not feasible or if a greater pressure reduction rate is desired, turn valve (3) to vent.

CAUTION: During steps No. 1 and 2 observe gauge (18) to avoid a pressure difference between chambers in excess of 3 to 5 psi. If the He chamber exceeds the LH_2 chamber by this amount, close valve (33) and open valve (5) to allow the pressure to decay to ambient.

Plan No. 2 (Assuming the High Pressure is Caused by the He Chamber Pressure)

1. Reduce the pressure setting on regulator (14).

2. Open valve (5) and allow the pressure to decay to ambient. (This is possible only if this line has been connected to the vent in preparation for this emergency condition.)

CAUTION: Observe gauge (18) to avoid a pressure differential between chambers in excess of 3 to 5 psi. (See Sections 2.3.5.2 and 2.3.5.3.)

Plan No. 3

Open valves 5 and 7 simultaneously and slowly, permitting both chambers to vent down without causing a differential pressure to be observed on gauge (18). (This is possible only if the lines from valves 5 and 7 can be used for venting these gases safely.)

2.3.5.2 Overpressurization of LH_2 Chamber

This condition can only occur when the bladder is full and is fully expanded against the inner tank. The bladder may be ruptured if the pressure within the bladder (LH_2 chamber) exceeds the pressure outside the bladder (helium expulsion chamber) by 3 to 5 psi. This condition is observed by comparing the pressures indicated on gauge (18).

Emergency action to protect the bladder requires turning valve (3) to "vent" position, thereby allowing the auto vent valve (28) to vent, decaying the control pressure in valve (30) and opening the valve to permit full venting of the pressure in the bladder.

2.3.5.3 Overpressurization of Helium Pressure Chamber

This condition can only occur when the bladder is completely empty and is collapsed against the helium bottle. The bladder may be ruptured if the pressure outside the bladder (helium pressure chamber) exceeds the pressure inside the bladder (LH_2 chamber) by 3 to 5 psi. This condition is observed by comparing the pressure indicated on gauge (18).

Emergency action to protect the bladder requires turning valve (6) to the "on" position, permitting the excess helium pressure to enter the bladder (LH_2 chamber) and equalize the pressure within and without the bladder. An alternate action is identical to Plan No. 2 of 2.3.5.1.

2.4 Principle of Operation

2.4.1 Inter-Relationship of Regulations (Figure 2.1)

The incorporation and arrangement of regulators (29), (30), and (32) is required to protect the bladder from rupture during the fill and expulsion of liquid hydrogen from the bladder. The rupture areas occur between the bladder mounting flange and the helium bottle surface during an expulsion cycle and between the mounting flange and the inner tank mounting neck fitting during a fill cycle. These rupture areas are narrow circumferential clearance gaps required to install the bladder (Figure 2.6).

A detail description of the inter-relationship of the regulators is found in paragraphs 2.4.1.1 and 2.4.1.2 and 2.4.1.3 and Figure 2.4. In general, regulator (32) is a two-stage regulator reducing the 2,100 psi helium pressure down for use by the system and to work in conjunction with regulator (29) and (30). Regulator (29) has essentially the function to protect the bladder from rupture during the expulsion cycle. Regulator (30) primary purpose is to protect the bladder from rupture during a fill cycle.

The purpose of the system is to provide He pressure to a bag which expels LH_2. It must be possible to regulate the He pressure through 5 to 60 psig range and never exceed 3 to 5 psi above the H_2 pressure within the bag. In addition, the H_2 pressure must not exceed the He pressure by 3 to 5 psi.

2.4.1.1 Two-Stage Regulator (32)

Regulator (32) is a two-stage regulator which accepts He gas at an inlet pressure range of 2,100 to 400 psi at the first stage. The first stage reduces the inlet pressure to 200 $\pm$ 50 psi. This pressure is available at two ports, one external for other systems and one internal at the inlet of the second stage. The second stage regulator reduces the 200 $\pm$ 50 psi to 5 to 60 psi through the use of a loaded dewar. The dewar loading pressure is supplied by the hand-loaded regulator (14) which thus sets the He pressure outside the bag. Regulator (32) in conjunction with regulator (29) prevents the He pressure from exceeding the H_2 pressure by 3 $\pm$ .5 psi. Part of the 3 $\pm$ .5 psi differential is eliminated in regulator (32) by the use of a spring-loaded part which reduces the outlet pressure to part "O_2" by 1 to 2 psi below the pressure supplied to the control port "C" by regulator (29).

2.4.1.2 Empty Bladder Relief Regulator (29)

Empty bladder relief regulator (29) contains a spring which exerts a force against the control port dome of 3 $\pm$ .5 psig. The effect of this spring is to permit full flow of He gas from the inlet to the outlet until the H_2 control pressure exceeds the inlet pressure by the spring pressure. At this time, the He flow through regulator (29) to regulator (32) is stopped, thus preventing additional He pressurization of the tank. In this manner, the differential pressure across the bag of 3 $\pm$ .5 psi is not exceeded. If the control pressure (LH_2 chamber pressure) was to drop, regulator (29) would vent off the excess pressure from the outlet line and indirectly permit the helium pressure chamber outside the bladder to be reduced.

2.4.1.3 Full Bladder Relief Valve (30)

Full bladder relief valve (30) is a dome-loaded relief valve equipped with a 3 psi spring which controls the LH_2 pressure in the bladder relative to the He pressure outside the bladder. Anytime the H_2 pressure exceeds the He pressure by 3 psi, the valve opens and permits H_2 to vent to atmosphere. This condition can only occur when the bag is filled to capacity and the walls of the bag exert a pressure against the walls of the tank. During the expulsion cycle, the pressure in the He and H_2 volumes are equal. At the end of the expulsion cycle, the He pressure may exceed the H_2 pressure but this condition is limited by regulators (29) and (32).

2.4.2 Vacuum-Purge Procedure

It is essential that all lines, tanks, and system components which may come into contact with hydrogen gas or liquid be purged with an inert gas before hydrogen is permitted in the system. The purpose of a purge is to eliminate all air and oxygen and replace with an inert gas so that there is no possibility of the low temperature hydrogen freezing out crystals of oxygen. Helium gas is used for purge because its critical temperature is lower than hydrogen, thus remaining a gas when in contact with liquid hydrogen.

The technique of cycling the system with a vacuum prior to the helium gas fill provides a more complete and positive purge. Several complete cycles of vacuum and helium pressure fill provide assurance that the system will not contain an explosive mixture or frozen particle which might interfere with the operation of the valves.

Section 2.2.4 explains in detail the procedures in operating the valves to perform the vacuum purge.

2.4.3 Handling Liquid Hydrogen

Storage and transfer of liquid hydrogen and oxygen can be effected safely and easily be observing a few precautions. Salient considerations are:

1. Never allow the fluids to contact the skin. The extremely low temperature of the fluids will freeze the skin, causing severe frost bite. If splashed by LH_2 or LOX, get first aid at once. Liberal flushing of the frost-bitten areas with tap water at about 70°F is a good first aid. Any lingering irritation or discoloration deserves medical attention.

2. Never smoke in the area of oxygen or hydrogen equipment. Fires may be started by the combination of hydrogen and oxygen or oxygen and any organic substance in the presence of a spark.

3. When in use, keep all equipment in a well-ventilated area away from combustible materials. These materials tend to trap the gases and can be easily ignited at a later time. It is desirable to keep the test area as clean as possible. Do not allow equipment to accumulate in the test area.

4. Never confine liquid or low temperature (less than 0°F) gaseous hydrogen or oxygen in enclosed containers which are not provided with pressure relief valves. When the gases expand as a result of being heated, extreme pressures are built up which may ultimately cause severe damage.

2.5 Net Positive Pressure Head System

2.5.1 System Description

This section describes the operation and functional characteristics of the Net Positive Pressure Head system (NPPH). The NPPH system is similar to the NPSH (Net Positive Suction Head) system in that the measurement is identical, but the purpose is different. In both systems the measurement made is the difference between the actual total head pressure and the vapor pressure of a liquid at the outlet of a tank.

2.5.1.1 Purpose

The purpose in taking a measurement using the NPPH system is to provide assurance that the fluid being expelled from the tank is in a liquid condition. If zero or negative pressure is indicated by the NPPH system, then it is likely that the fluid in the tank is below the vapor pressure and that gas or a two-phase fluid is being expelled. A positive pressure will exist if the total head is greater than the vapor pressure of the liquid.

2.5.1.2 Principle

The pressure measurement produced by the NPPH system is dependent upon the vapor pressure of the liquid which is dependent upon the temperature condition of the liquid. The vapor pressure of a liquid follows a curve which increases with an increase in temperature. If the liquid is contained in a closed vessel, such as a vapor bulb, a condition of equilibrium exists when the pressure in the bulb equals the vapor pressure of the liquid for the particular temperature condition present. The NPPH is the differential pressure existing between the vapor pressure and the total head adjacent to the vapor bulb.

2.5.2 Equipment

2.5.2.1 Vapor Bulb

The bulb is the heart of the NPPH system and is located within the outlet line of the tank. It is a .294 O.D. stainless steel tube 2 inches in length. A 1/16" O.D. - .023 I.D. capillary tube connected to the bulb leaves the outlet line through a Conax connector and is connected to the NPPH system components and transducers on the back of the panel.

2.5.2.2 Total Head Tube

The liquid total head sensing tube is located in the outlet line adjacent to the vapor pressure bulb. The tube leaves the outlet line through a Conax connector and is connected to the one side of the differential pressure transducers opposite the vapor bulb pressure connection.

2.5.2.3 Expansion Tank (No. 25)

The expansion tank formed from two stainless steel welding caps provides 15.4 cubic inches additional volume in the vapor bulb system to keep the pressure within reasonable limits. With the tank in the system, the maximum pressure could be approximately 92 psi of hydrogen. Without the tank, the pressure would have to be 10,000 to 40,000 psi of gas in order to supply the required amount of hydrogen gas to the vapor bulb when the bulb was cooled down.

2.5.2.4 Pressure Gage

The pressure gage attached to the expansion tank is used to set the required pressure in the tank so as to produce the proper liquid level in the vapor bulb when it is cooled down.

2.5.2.5 Valves

2.5.2.5.1 H_2 Fill Shutoff Valve No. 8

Valve No. 8 is used to admit H_2 gas to the expansion tank. It is closed at the conclusion of the H_2 gas filling procedure.

2.5.2.5.2 Expansion Tank Shutoff Valve No. 9

Valve No. 9 isolates the pressure in the tank when it is desirable to do so. Normally, this valve can remain open.

2.5.2.5.3 Differential Pressure Equalizer Valve No. 10

Valve No. 10 connects the total head tube line and the vapor pressure line together to permit equalizing the pressure on each side of the transducer. This valve operates in conjunction with valve No. 12 but in opposite positions. When valve 10 is open, valve 12 should be closed, and vice versa.

2.5.2.5.4 Vapor Bulb Shutoff Valve No. 11

Valve No. 11 is located in the system to permit the removal of the transducers. This valve is normally open unless closed for removing a transducer.

2.5.2.5.5 Total Head Shutoff Valve No. 12

Valve No. 12 is used to allow the total head pressure to act upon the transducers. It is normally closed except when the expulsion tank is full of LH_2 and a test is in process. It is operated in conjunction with valve No. 10 but in the opposite position. When valve No. 10 is open, valve No. 12 is closed, and vice versa.

CAUTION: Valve No. 10 is always opened first before valve 12 is closed to prevent unequal pressures from acting across the transducers. Valve No. 12 is always opened before valve No. 10 is closed.

2.5.2.5.6 Transducer Isolator Valve No. 48

Valve No. 48 is located in the system to permit the removal of the transducers. This valve is normally open unless closed for removing a transducer.

2.5.2.5.7 Fill Connector No. 23

The NPPH system is filled with hydrogen gas under pressure through fill connector No. 23.

2.5.2.6 Instrumentation

Two Northam differential pressure transducers may be used to measure the pressure in the vapor pressure bulb. One instrument records the pressure from 0 to $\pm$ 15 psi and the other from 0 to $\pm$ .15 psi. Other types of differential pressure transducers may be used, but the Northam type has an overpressurization feature for protection.

2.5.3 System Preparation

2.5.3.1 Cleaning

The NPPH system should be LOX cleaned according to Beech Spec B.S. 8503A.

2.5.3.2 Purging

The system must be purged before filling with hydrogen. The vacuum-helium fill technique is used to purge the lines and tank.

CAUTION: Prior to pulling a vacuum valve, Nos. 8, 9, 10, 11, 12, and 48 must be open and valve No. 12 closed.

The NPPH system could be purged at the same time as the expulsion tank is purged by opening all the valves Nos. 8, 9, 10, 11, 12, and 48.

This vacuum-fill purge cycle should be accomplished several times to assure the elimination of air.

Following the purging process, the tank and system are ready for filling with hydrogen under pressure.

2.5.3.3 Inspection

Rigid inspection procedures should be maintained to assure a clear and leak-tight system. The validity of the data is dependent upon the leak tightness of the NPPH system tubes and fittings.

2.5.3.4 Transducer Calibration

The transducer must be calibrated with known pressures before being used in a test.

2.5.3.5 Pressurizing System

Before pressurizing the NPPH system, close valve 12 and open valves No. 9, 10, 11, and 48. Connect the source of H_2 pressure and open valve No. 8. Pressurize the systems with pure H_2 gas to a pressure of 92 psi at 70°F ambient temperature. If the temperature is other than 70°, the pressure should be adjusted accordingly. The pressure should be checked after the gas has a period of time to stabilize. When the system is properly pressurized, close fill valve No. 8 and disconnect the fill connector. The system is now ready for operation.

2.5.4 Operation

The following steps should be followed in preparation for using the data from the NPPH system during an expulsion test.

1. Check to see that valve No. 12 and 8 are closed and valves No. 9, 10, 11, and 48 are open.

2. Fill the expulsion tank with LH_2 and allow the vapor bulb to cool down, thus lowering the pressure in the NPPH system and liquefying the H_2 gas in the bulb.

3. When the vapor bulb has cooled down and stabilized and the tank is full, the pressure on the total head tube and the pressure in the vapor bulb should be equal. At this time, open valve No. 12 and close valve No. 10.

4. The transducers should now read the differential pressure across the total head and vapor bulb. If the LH_2 and system have stabilized, the differential pressure should be zero. Close valve 9.

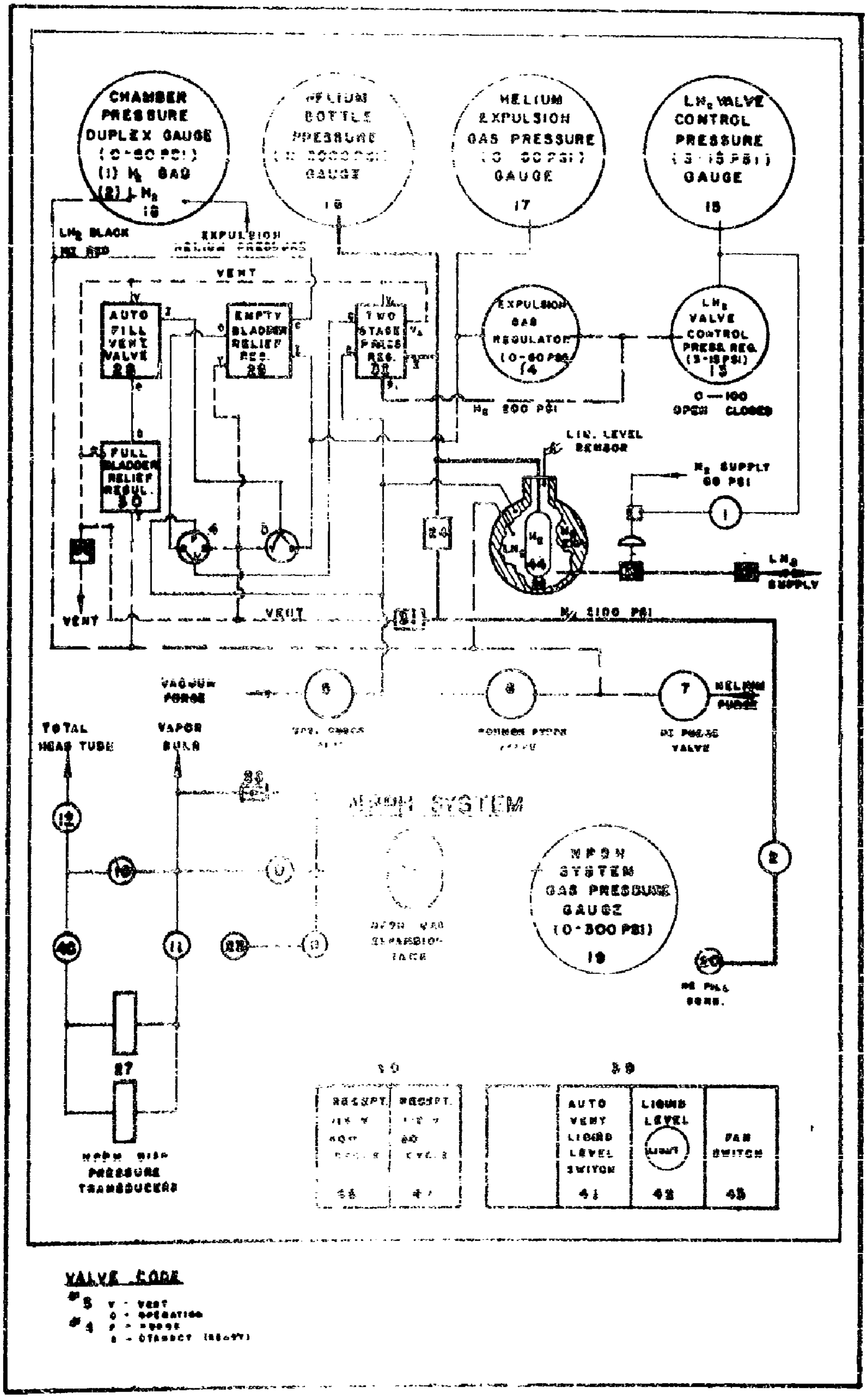
5. When the expulsion tank is pressurized, the NPPH system should indicate an increasing differential pressure. During an expulsion cycle, the differential pressure should be maintained by increasing the pressure on the LH_2 in the tank.

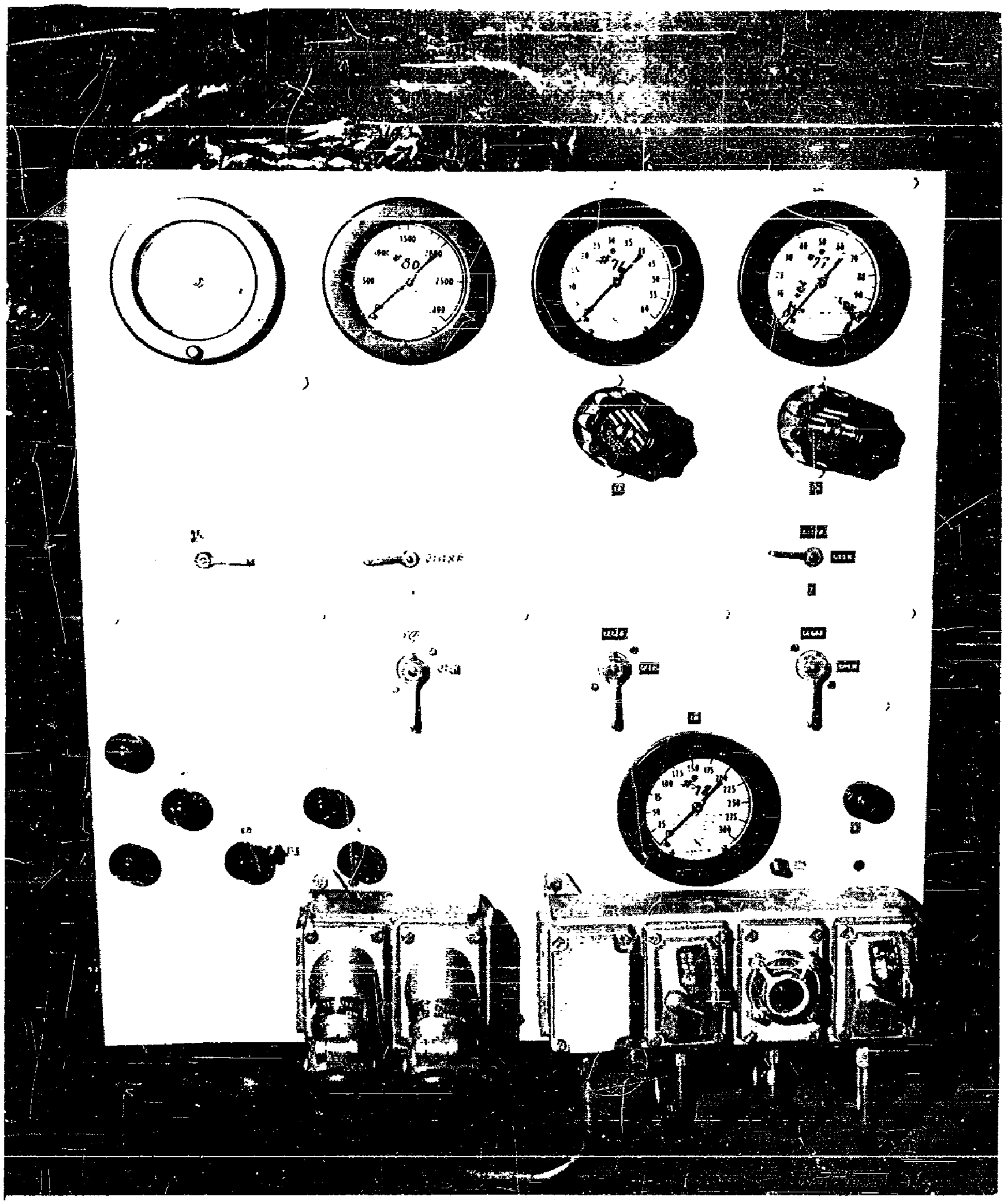
   NOTE: As long as the differential pressure indicates that the total head tube pressure is greater than the vapor bulb, liquid can be assured in the outlet line of the tank.

6. When the LH_2 has been fully expelled, the NPPH system should be returned to its normal condition. Open valves Nos. 9 and 10 and close valve No. 12.

CAUTION (1): Step No. 6 must be accomplished prior to the vapor bulb warming up; otherwise, an excessive pressure would occur on the vapor bulb side of the differential pressure transducer. The Northam transducer would not be affected, but other types of strain gages could be damaged.

CAUTION (2): Always open valve No. 10 before closing valve No. 12 to prevent unequal pressures from acting across the transducers. Valve No. 12 must be opened before closing valve No. 10.


CHAMBER PRESSURE DUPLEX GAUGE (0-60 PSI) (1) H_2 GAS (2) LH_2
16
HELIUM BOTTLE PRESSURE GAUGE
18
HELIUM EXPULSION GAS PRESSURE (0-60 PSI) GAUGE
17
LH_2 VALVE CONTROL PRESSURE (3-15 PSI) GAUGE
15
LH_2 BLACK
HE RED
EXPULSION HELIUM PRESSURE
VENT
AUTO FILL VENT VALVE
28
EMPTY BLADDER RELIEF REG.
29
TWO STAGE PRESS REG.
EXPULSION GAS REGULATOR (0-60 PSI)
14
LH_2 VALVE CONTROL PRESS. REG. (3-15 PSI)
13
0 — 100
OPEN CLOSED
H_2 200 PSI
LIQ. LEVEL SENSOR
N_2 SUPPLY 60 PSI
FULL BLADDER RELIEF REGUL.
30
24
44
LH_2 SUPPLY
VENT
VENT
N_2 2100 PSI
VACUUM PORGE
HELIUM PURGE
TOTAL HEAD TUBE
VAPOR BULB
HE PURGE VALVE
NPSH SYSTEM
NPSH SYSTEM GAS PRESSURE GAUGE (0-300 PSI)
19
HE FILL CONN.
27
NPSH DIFF PRESSURE TRANSDUCERS
40
39
AUTO VENT LIQUID LEVEL SWITCH
41
LIQUID LEVEL
42
FAN SWITCH
43
VALVE CODE
V - VENT
O - OPERATION
P - PURGE
S - STANDBY



SYSTEM COMPONENTS NUMBER CORRELATION CHART

Code No.	Component Description			
	Item	Size	Manufacturer	Part No.
1	Valve, Shutoff	1/4 OD Tube	Republic	A320HTX4-D
2	Valve, Shutoff	1/4 OD Swagelok	Hoke	D1189
3	Valve, 2-Way	1/4 OD Tube	Republic	A23-1X4-D
4	Valve, 3-Way	1/4 OD Tube	Republic	A324-111X4-D
5	Valve, Shutoff	1/2 OD Tube	Republic	A320HTX8-D
6	Valve, Shutoff	1/2 OD Tube	Republic	A320HTX8-D
7	Valve, Shutoff	1/2 OD Tube	Republic	A320HTX8-D
8	Valve, Shutoff	1/4 OD Swagelok	Hoke	D1189
9	Valve, Shutoff	1/4 OD Swagelok	Hoke	D1189
10	Valve, Shutoff	1/4 OD Swagelok	Hoke	D1189
11	Valve, Shutoff	1/4 OD Swagelok	Hoke	D1189
12	Valve, Shutoff	1/4 OD Swagelok	Hoke	D1189
13	Regulator, Hand	1/4 OD Tube	APCO	132300X1
14	Regulator, Hand	1/4 OD Tube	APCO	132300X2
15	Gauge, 3-15 psi	1/4 MNPT	Ashcraft	1377A-XRP
16	Gauge, 0-3000 psi	1/2 MNPT	Ashcraft	1377D
17	Gauge, 0-60 psi	1/4 MNPT	Ashcraft	1377A
18	Gauge, -30" Hg-60 psi	1/4 MNPT	Ashcraft	1339AC
19	Gauge, 0-300 psi	1/4 MNPT	Ashcraft	1337A
20	Connector, Fill	1/4 OD Tube	Parker	4WEBTX
21	Connector, He Purge	1/2 OD Tube		
22	Connector, Vac. Purge	1/2 OD Tube		
23	Connector, NPSH Fill	1/4 OD Tube	Parker	4WEBTX
24	Filter	1/4 OD Tube	Bendix	10P-28722T-4
25	Tank, Expansion	3" Weld Caps	Beech	7035-1004-177
26	Valve, Check	1/4 OD Swagelok	Hoke	1257
27	Transducers, Press.	15 psi, .15 psi	Northam	DP-7
28	Valve, Elec. Sol.	1/4 OD Tube	Hoke	B95A443
29	Regulator	1/4 NPT	APCO	122900-X1
30	Regulator, Relief	3/4 NPT	APCO	133000X1

FIGURE [illegible]
INTER-RELATIONSHIP OF REGULATORS
(SIMPLIFIED DIAGRAM)

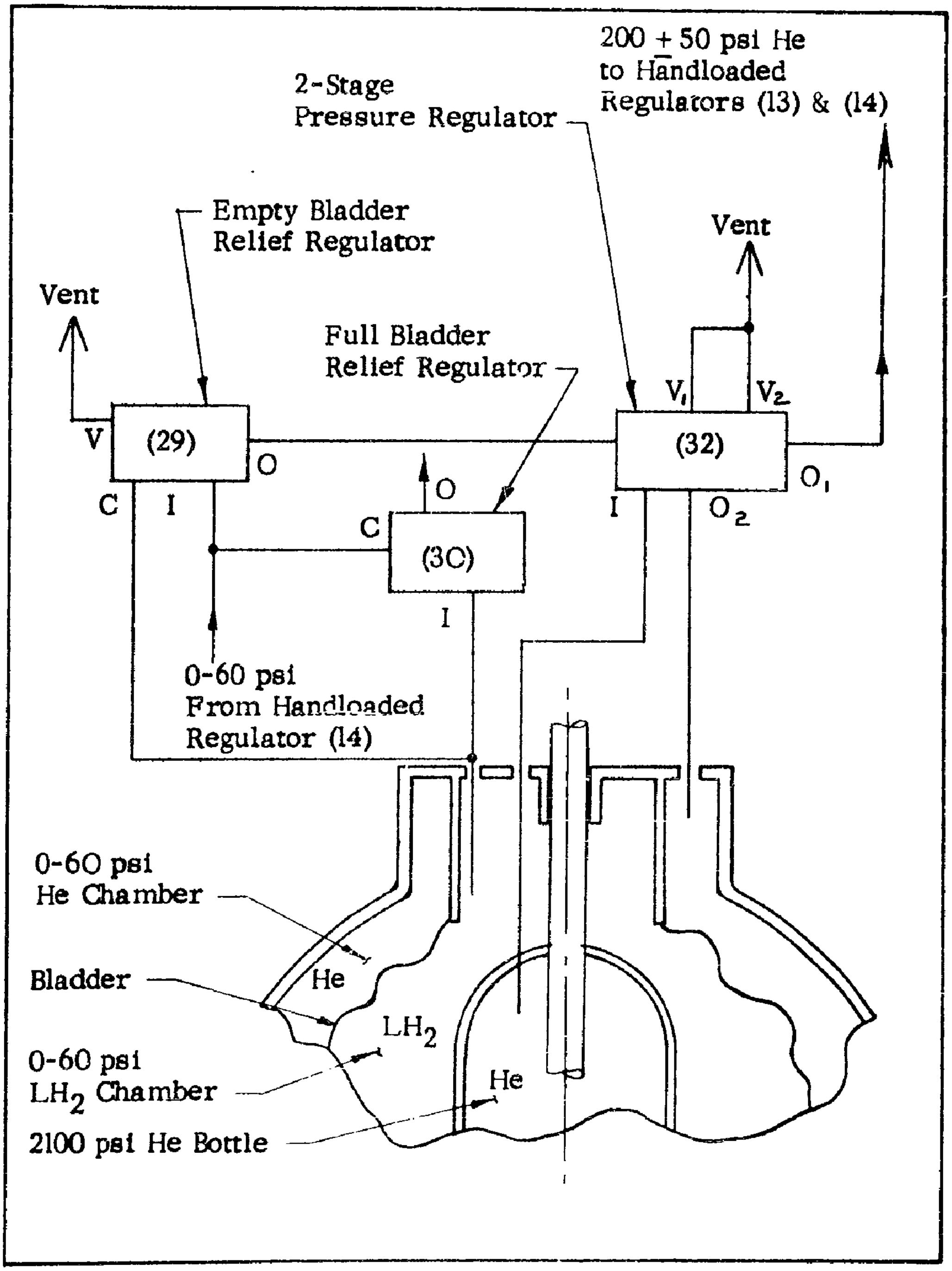


FIGURE 3.[illegible]
PLUMBING INSTALLATION SCHEMATIC

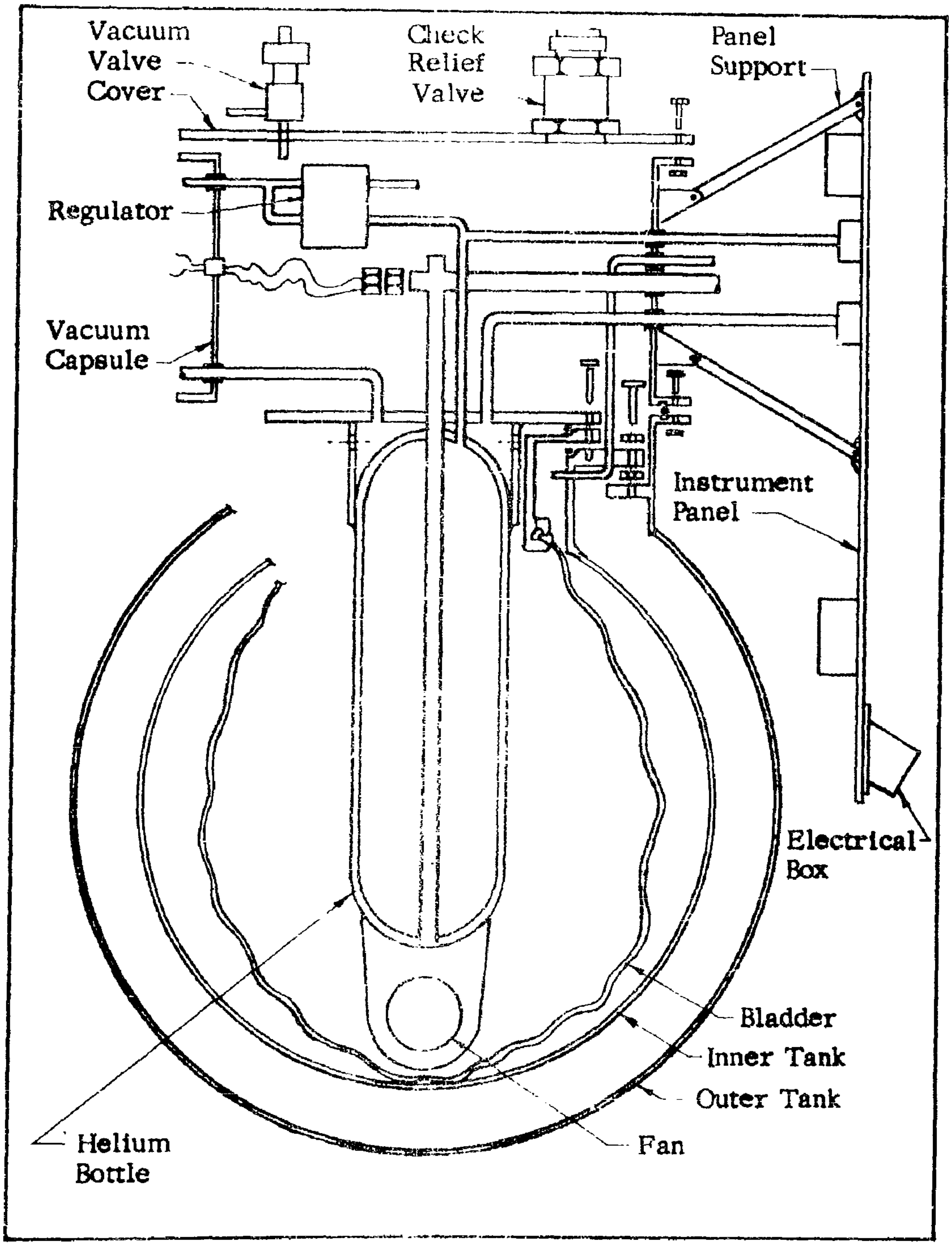


FIGURE [illegible]
INSTALLATION OF BLADDER

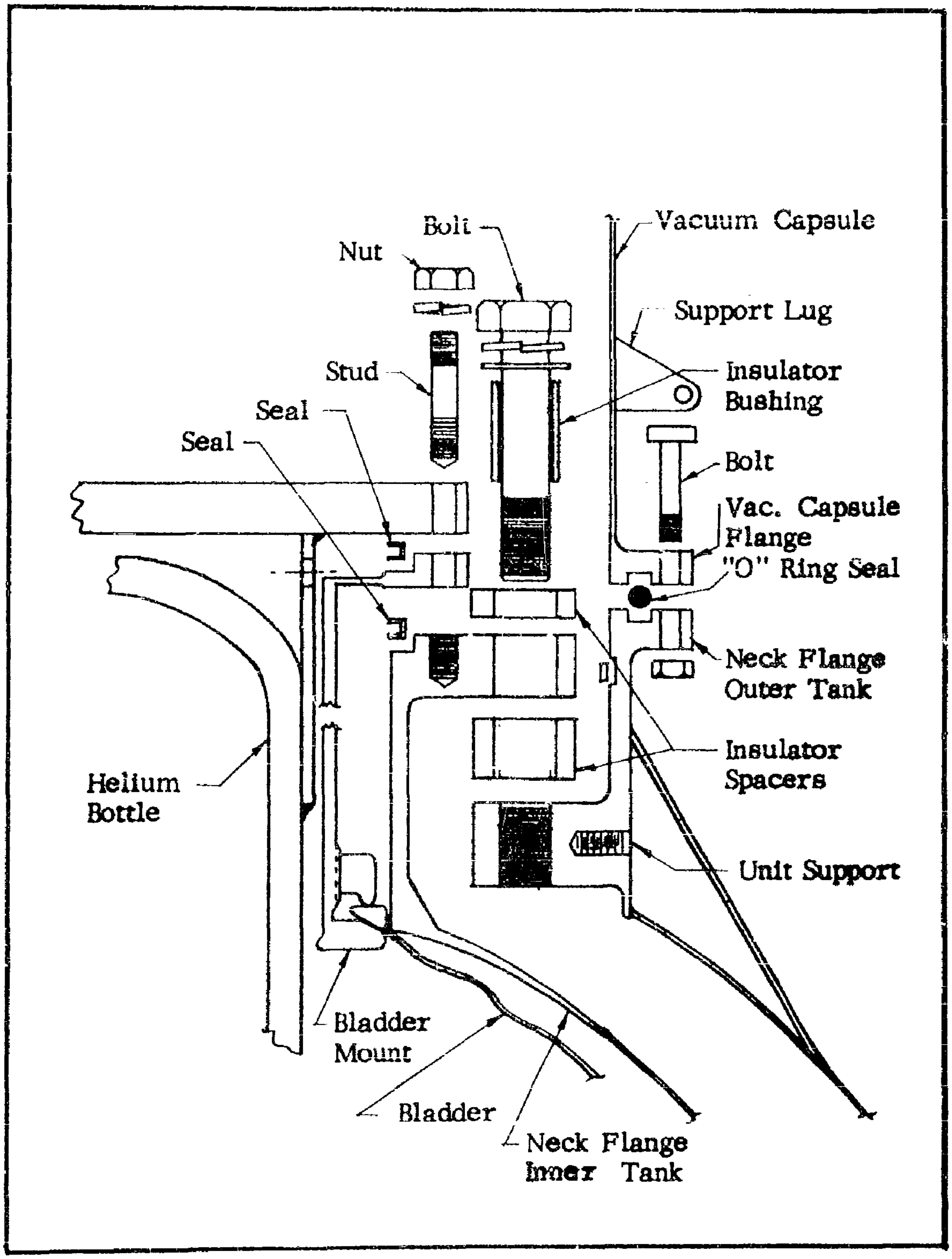


FIGURE 2.7
ELECTRICAL DIAGRAM (2 PHASE FAN - UNIT 1)

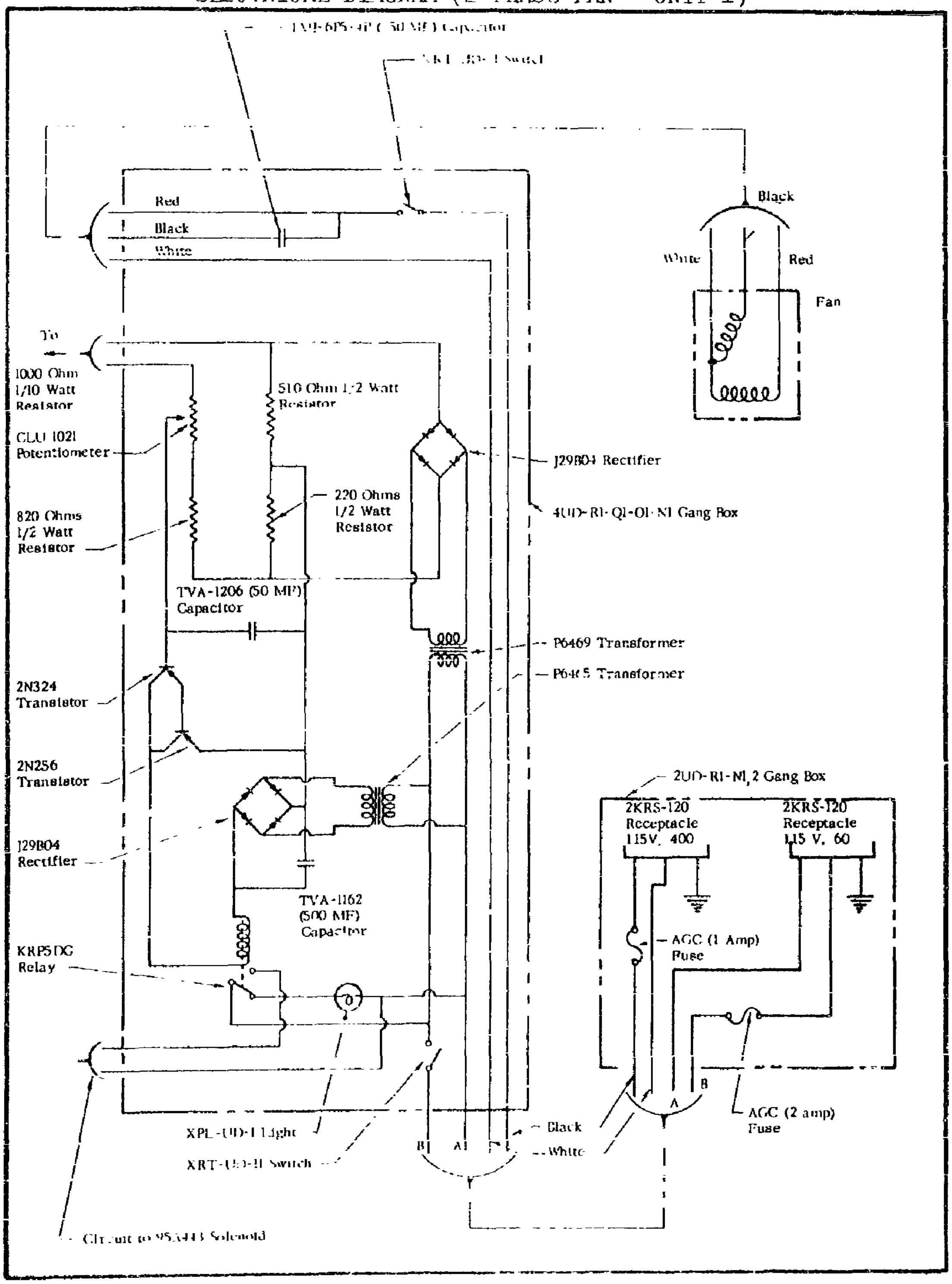


FIGURE 2.7
ELECTRICAL DIAGRAM (3 PHASE FAN - UNIT 2)

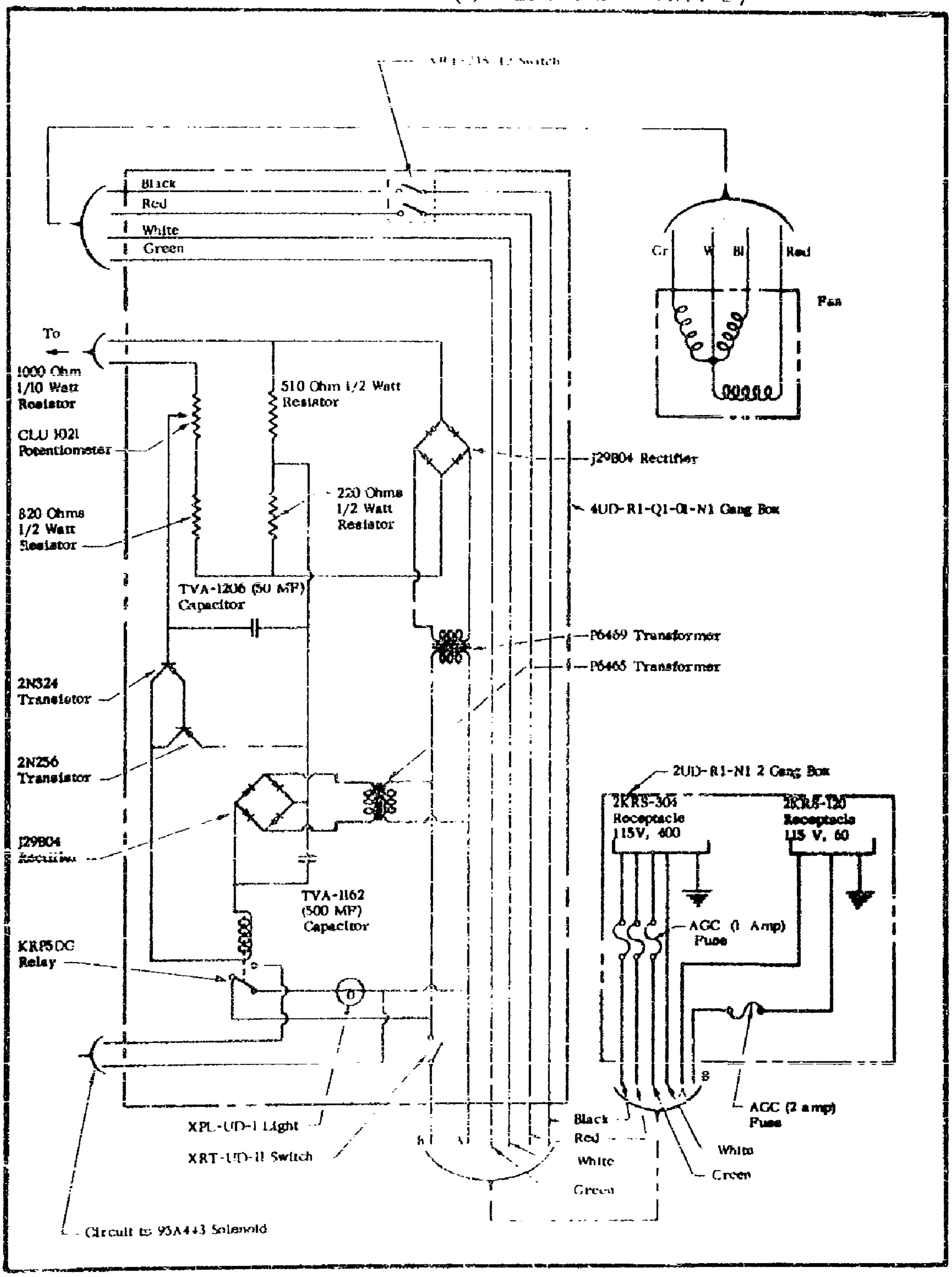


FIGURE 2.7
ELECTRICAL DIAGRAM (3 PHASE FAN - UNIT 2)

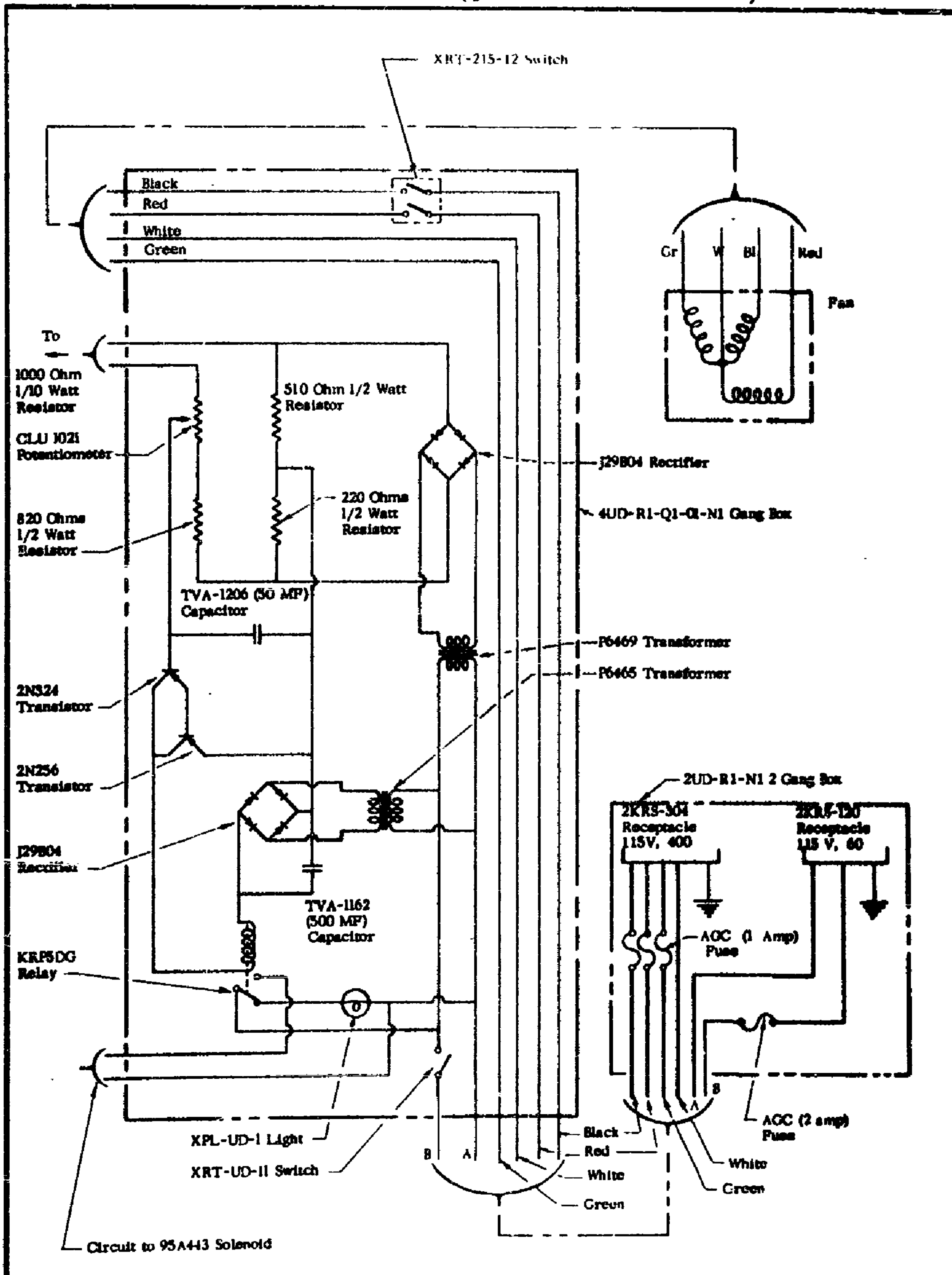
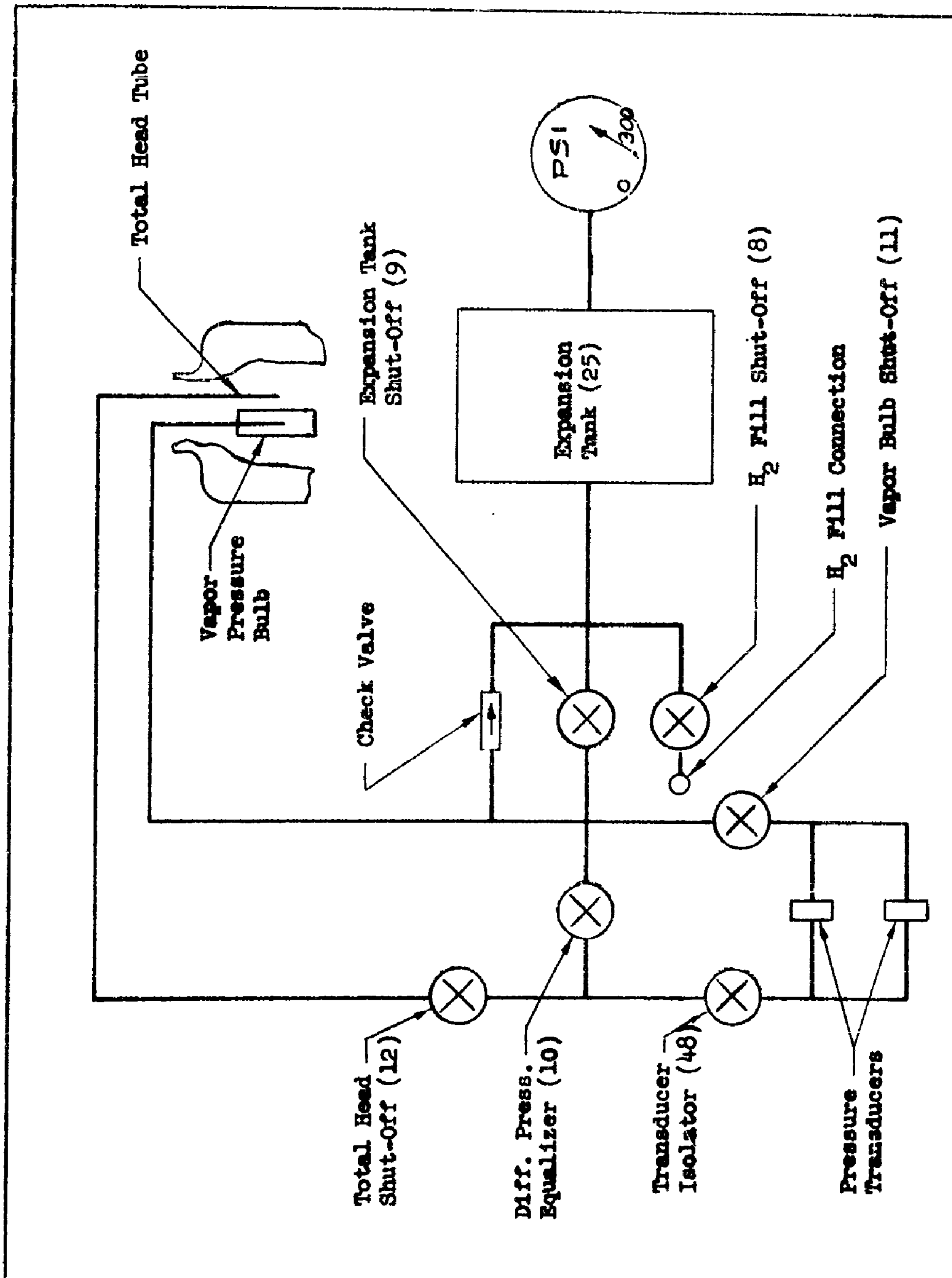


FIGURE 2.8
NET POSITIVE PRESSURE HEAD SYSTEM



3.0 PROTOTYPE TESTING

The planned prototype testing program consisted of three separate phases. The first testing involved the hydrostatic testing of the helium bottle and the inner tank. The second test, which involved the completed unit, concerned measuring the boil-off gases as related to the insulation qualities of the dewar. The third test was set up to measure the operating characteristics of the positive expulsion unit as a whole.

3.1 Hydrostatic Testing

Prior to cleaning and final assembly, the high pressure helium bottle and the inner tank shell assembly were tested hydrostatically.

3.1.1 Hydrostatic Test of Inner Tank Shell

The inner tank shell was pressure tested through the use of the test setup shown by Figure 3.1. The inner tank shell assembly was filled with water. The flange was then bolted in place. The system was pressurized through the use of a Blackhawk (P76) hand pump. Proof pressure of 117 psig was held for three minutes. No deformation or leakage occurred. The unit was then checked for leakage through the use of a helium leak detector. The unit was pressurized to 75 psig using helium gas for two minutes. No leakage was detected.

3.1.2 Hydrostatic Test of High Pressure Helium Bottle

The high pressure helium bottle was pressure tested through the use of the test setup shown by Figure 3.2. The bottle was filled with water. The flange was bolted in place, and the unit was pressurized to 3,000 psig through the use of a Blackhawk (P76) hand pump. The pressure was held for 3 minutes. No deformation of leakage occurred. A helium leakage test was then conducted by pressurizing the unit to 2100 psig using helium gas. No detectable leakage was noted when the unit was checked using a helium leak detector.

3.2 Boil-Off Gas Measurement

This test was established to verify the design calculations for the heat transfer through the insulated tank wall and the solid conduction heat transfer through the lines and fittings. The bladder was installed, but expulsion was not practiced during this test. The gas boil-off rate, temperature, and pressure of the gas was recorded. The test was conducted with a tank pressure of 10 psig.

The boil-off gas from the liquid hydrogen was permitted to warm up to ambient pressure and temperature and was passed through a wet test meter. The tank was filled and the test was begun when approximately 75% of the liquid remained. Maintaining the pressure in the tank at 10 psi by means of a relief valve, the boil-off was measured for periods of 5 to 10 minutes.

The theoretical calculations showed the boil-off to be as high as 71 CFH with a full tank and 48 CFH when half full at standard pressure and temperature. The results of the actual testing for two test runs showed a rate of 55 CFH. Since the boil-off rate is dependent on factors, such as quantity of liquid hydrogen in the tank, it is possible that the 71 CFH rate might be expected under some conditions.

Although the rate of boil-off gas compared favorably with the design and theoretical calculations, improvement should be possible by further design refinements and improved insulation.

3.3 Operational Characteristics of Positive Expulsion System

The operational characteristics of the positive expulsion system are directly dependent upon the ability of the system to maintain a net positive pressure head (NPPH) at the outlet of the tank. The primary purpose of the test described in this section is to establish performance curves of NPPH during liquid hydrogen expulsion. The curves should reflect time versus the pressure required to maintain a minimum of 18 inches of liquid hydrogen NPPH (33 feet of LH_2 equals 1 psi). Figure 3.7 illustrates typical curves that may be drawn as a result of these tests.

The following procedures were used to obtain the desired results from the test. Figure 3.6 illustrates the setup used for this test.

1. The positive expulsion unit was prepared for operation according to the operator's manual, Model 7035, which is included, in part, in Section 2.0 of this report.

2. Additional test apparatus was required for the test which included a heater, pressure and temperature transducers, and flowmeter in the expulsion line, as well as an additional filter and electric valve.

3. The instruments were connected with the respective recorders located in the "bunker" and control room.

(a) The NPPH transducers were connected to a Brush 2-channel recorder.
(b) The pressure and temperature transducers in the outlet line were connected to a Midwestern oscillograph.
(c) The Waugh flowmeter was read on a Beckman Berkeley digital counter.

4. The bladder was filled with liquid hydrogen directly from a 6,000 liter storage dewar, according to the instructions for filling.

5. The fill valve was closed and the pressure in the tank was raised to 5 psi.

6. The recorders were started and the outlet valve was open, permitting the liquid hydrogen to be expelled. The fluid was passed through a coil submerged in warm water to be sure of a single phase gas passing through the flowmeter.

7. When the NPPH dropped to 18 inches of liquid hydrogen head as sensed by NPPH transducer, the tank pressure was increased 10 psig by means of the tank pressure regulator (14) and indicated by the chamber pressure gage (18) (reference Figure 2.1).

   This procedure (Item 7) was repeated until the bladder had fully expelled the contained LH_2 or the maximum permissible 60 psi was reached in the tank.

The procedure outlined above was planned to be followed first with the equilibration fan operating during a complete expulsion cycle and then without the fan running. The purpose of this alternate test is to determine the practical value of circulating the fluid in the bladder to maintain a more constant temperature throughout. See Testing Summary for problems involved in completing this part of test.

3.4 Testing Summary

The test program, Section 3.3, was pursued continuously for a period of two months. Because of the problems with the regulator (32) and the bladders, satisfactory completion of all of the tests was not possible. Section 4.4, Summary of Problem Areas, and Section 5.0, Recommendations and Conclusions, describe in detail the problems and possible solutions.

During the course of the prototype testing program, the performance of the two-stage cryogenic pressure regulator failed to consistently meet the expectation of the originally planned program. This regulator was returned to the factory several times for extensive rework, but failed on each occasion to deliver the required regulated helium expulsion pressure for proper system operation. On some occasions it was necessary to physically vibrate the regulator to cause regulation. In other cases the regulator would perform in a warm condition but not when cooled down to LH_2 temperature. This regulator is installed in the vacuum chamber above the tank and receives the helium gas at -420°F directly from the helium bottle submerged in LH_2. This location is essential so that the gas is at liquid hydrogen temperature when it is used for pressurizing the bladder.

When the regulator continued to fail to perform after the many reworks and negotiations with the contractor, a final run was attempted by bypassing the regulator. This method is not completely satisfactory because it requires that the helium gas pass out of the vacuum chamber with the resulting disadvantages of warming up. Pressurization gas at a temperature warmer than liquid hydrogen adds heat to the LH_2, resulting in boil-off or tending to destroy the NPPH advantage which is required for expulsion. This particular expulsion test was thwarted by reason of a bladder failure occuring after 1 or 2 cycles of operation.

The second major problem which made it impossible to obtain statistically valid results from the prepared test program was the early failure of the bladders. The bladders furnished for the unit proved to be incapable of supplying a sufficient number of cycles to provide any useful test data. The initial bladder was cycled 10 to 20 times during which time the instrumentation was calibrated and adjusted and the unit was checked for leakage. The second and third bladders failed during the second expulsion cycle. Section 4.1 of this report describes the bladder construction used in all three test assemblies. The configuration was selected on the basis of test results obtained during Phase I on three identical bladder cells and on the excellent workmanship displayed by the G. T. Schjeldahl Company in the fabrication of the Mylar bladders.

Most of the bladder failures occurred at the top near the mounting flange, although fabric tears occurred at other places in at least one membrane. The tearing of all three membranes at the top created a condition which prevented further expulsion of the liquid in the tank. Since the LH_2 is in the bladder and the expulsion is created by helium gas pressure on the outside of the bladder, an opening between these two chambers permits the LH_2 to be expelled through the opening into the helium pressurization chamber. Once the liquid is forced out of the top of the bladder, it is trapped from the outlet located in the bladder at the bottom. This event, which occurred when each bladder failed, caused a shortening of the test and necessarily prevented useful test data from being realized.

Because of the two basic problems discussed in detail above, useful NPPH data could not be obtained. It is anticipated that follow-on effort would help solve the regulator and bladder problems. The two positive expulsion units are therefore not completely operational at the present time.

FIGURE 3.1
HYDROSTATIC TEST OF INNER TANK SHELL

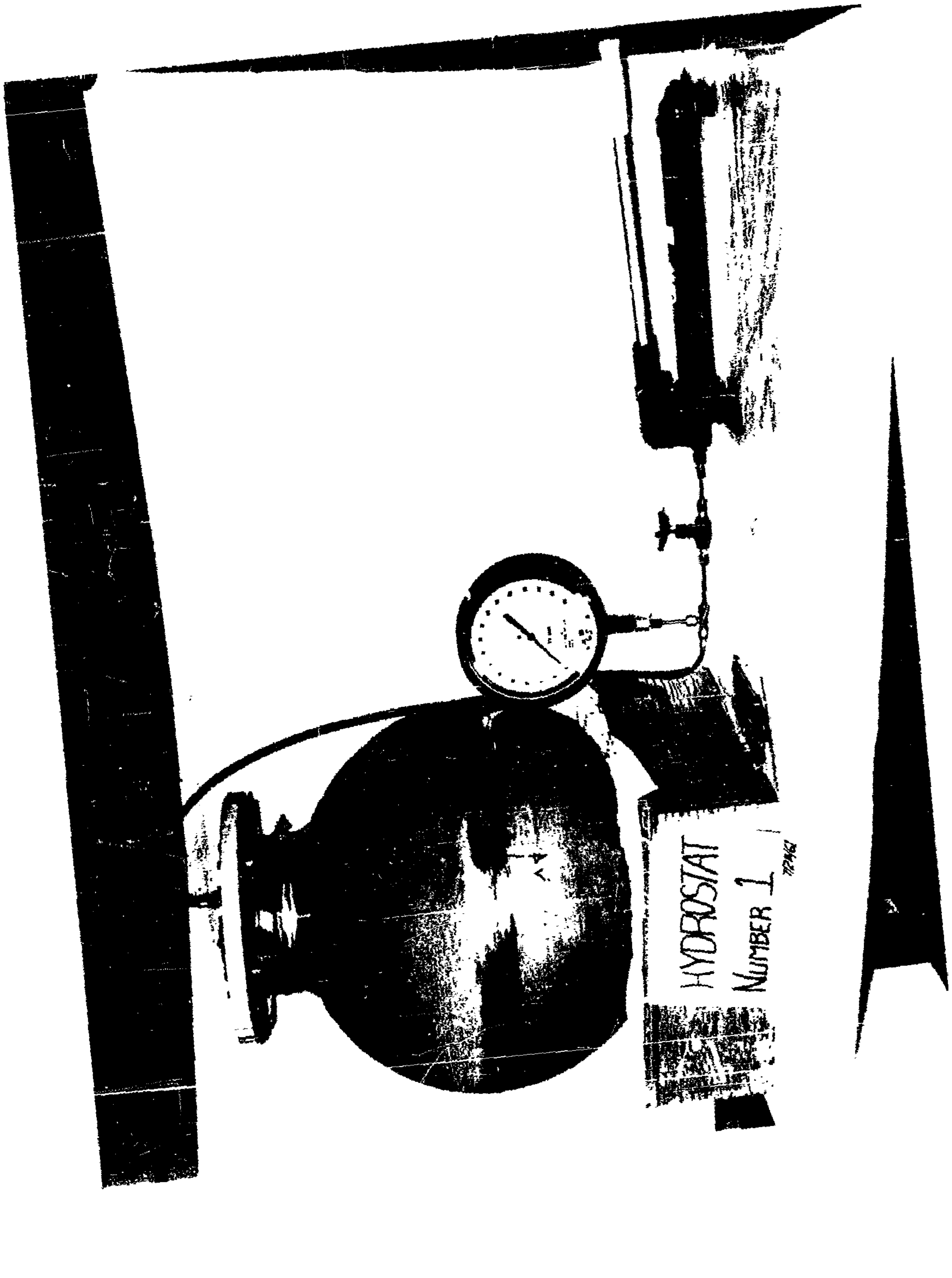


FIGURE 3.2
HYDROSTATIC TEST OF HIGH PRESSURE HELIUM BOTTLE

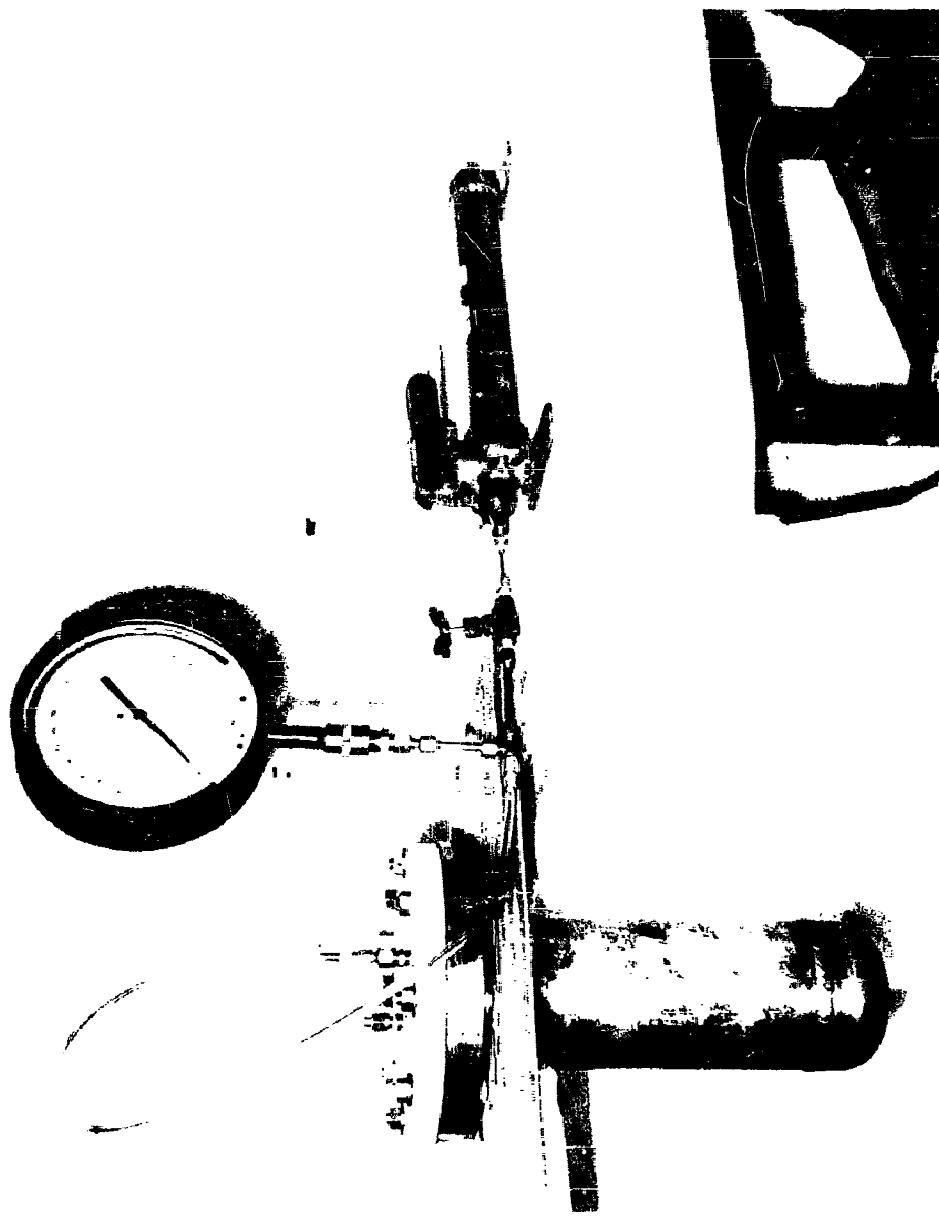


FIGURE [illegible].

PLUMBING SYSTEM

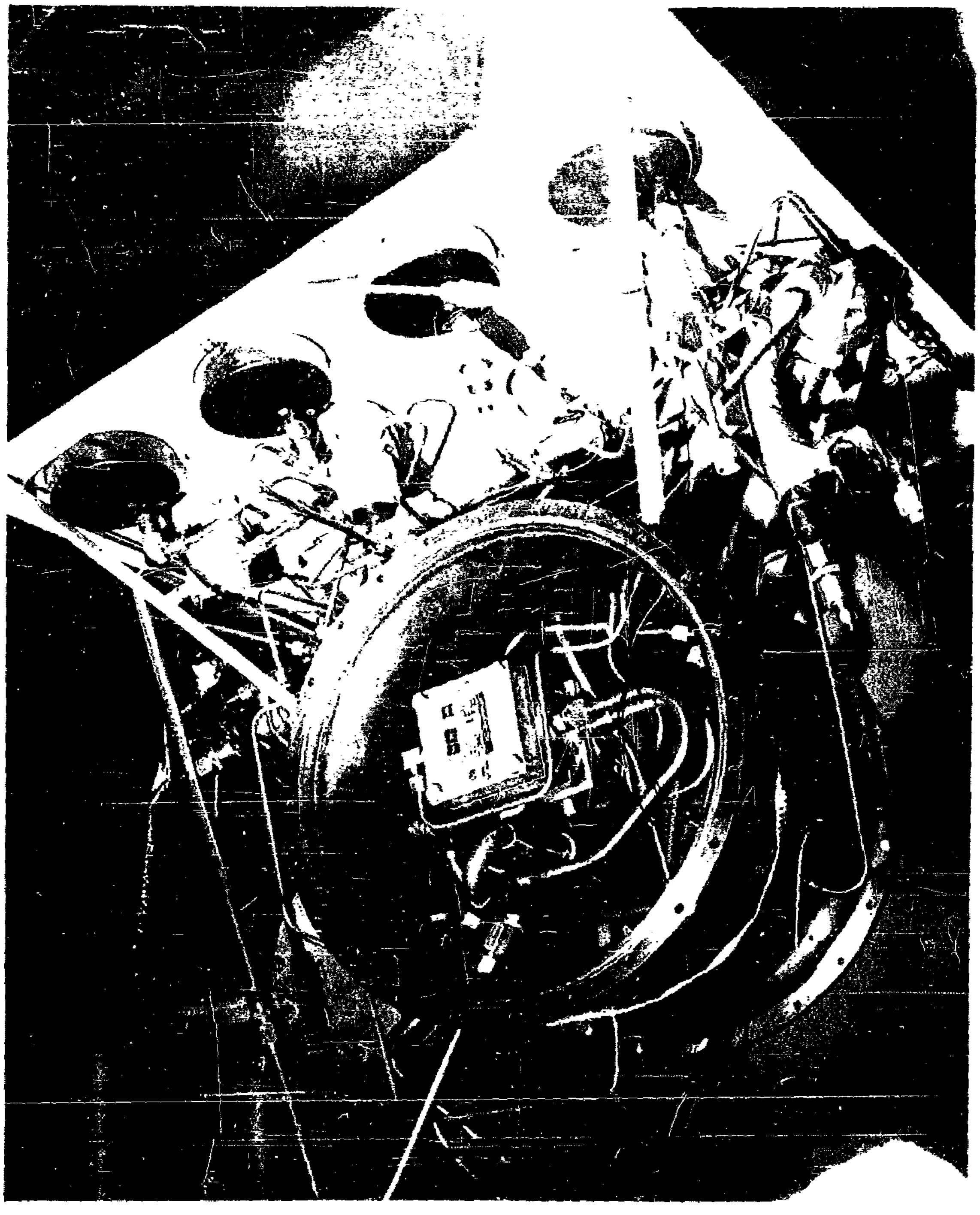


FIGURE 3.4
PLUMBING SYSTEM
RIGHT SIDE, REAR VIEW OF PANEL

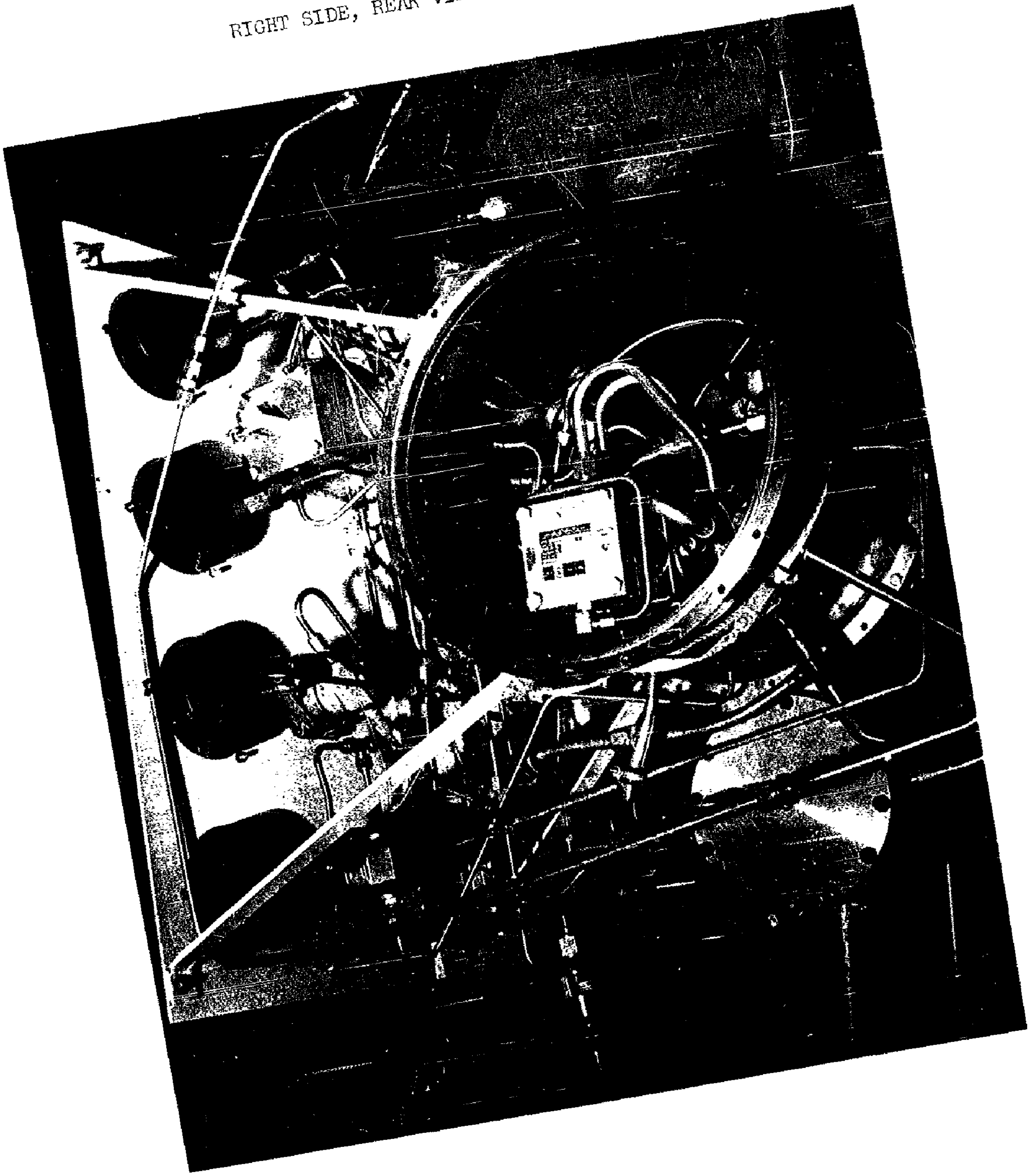


FIGURE 3.5

PROTOTYPE BLADDER ASSEMBLY

FIGURE 3.6
OPERATIONAL CHARACTERISTICS TEST SCHEMATIC

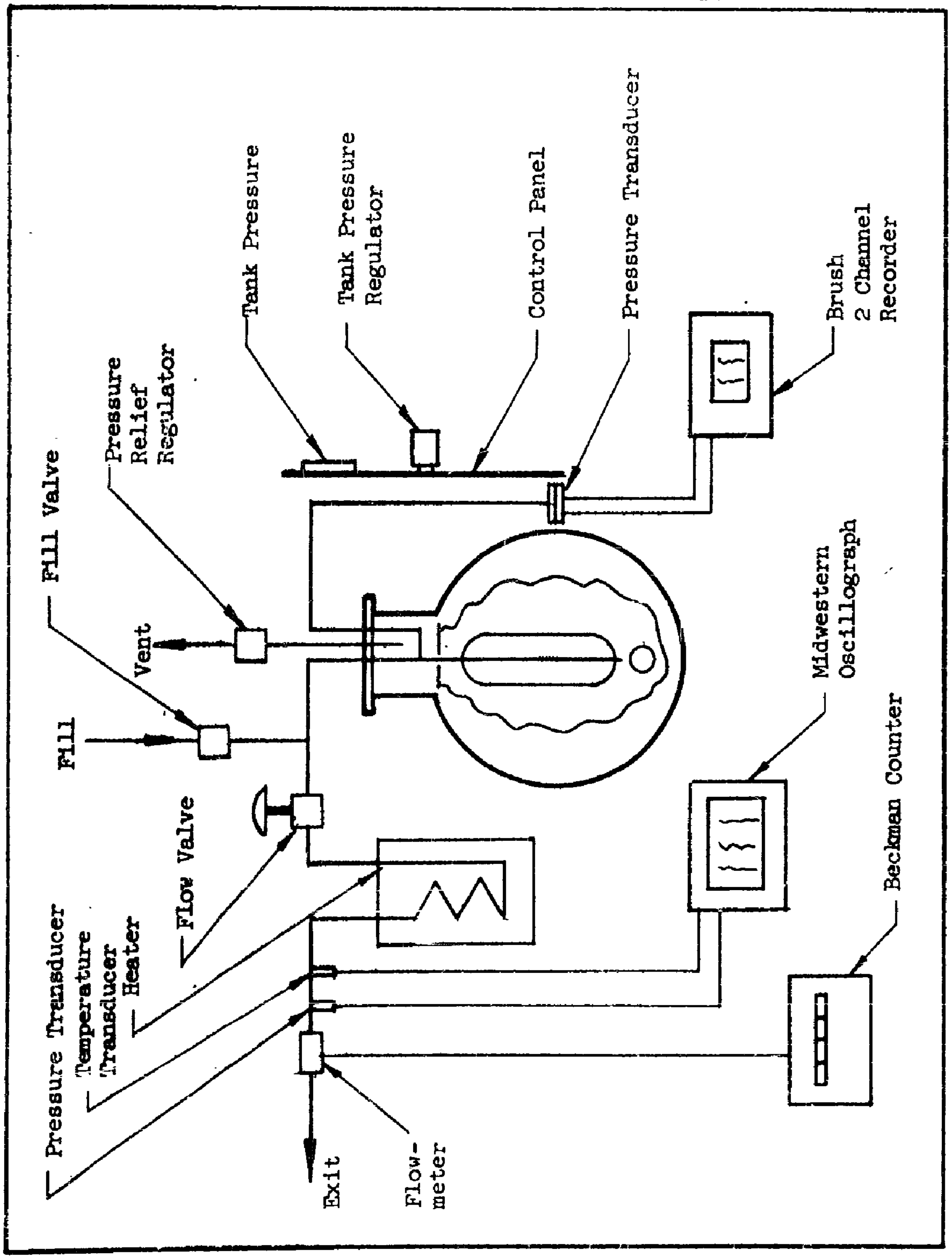
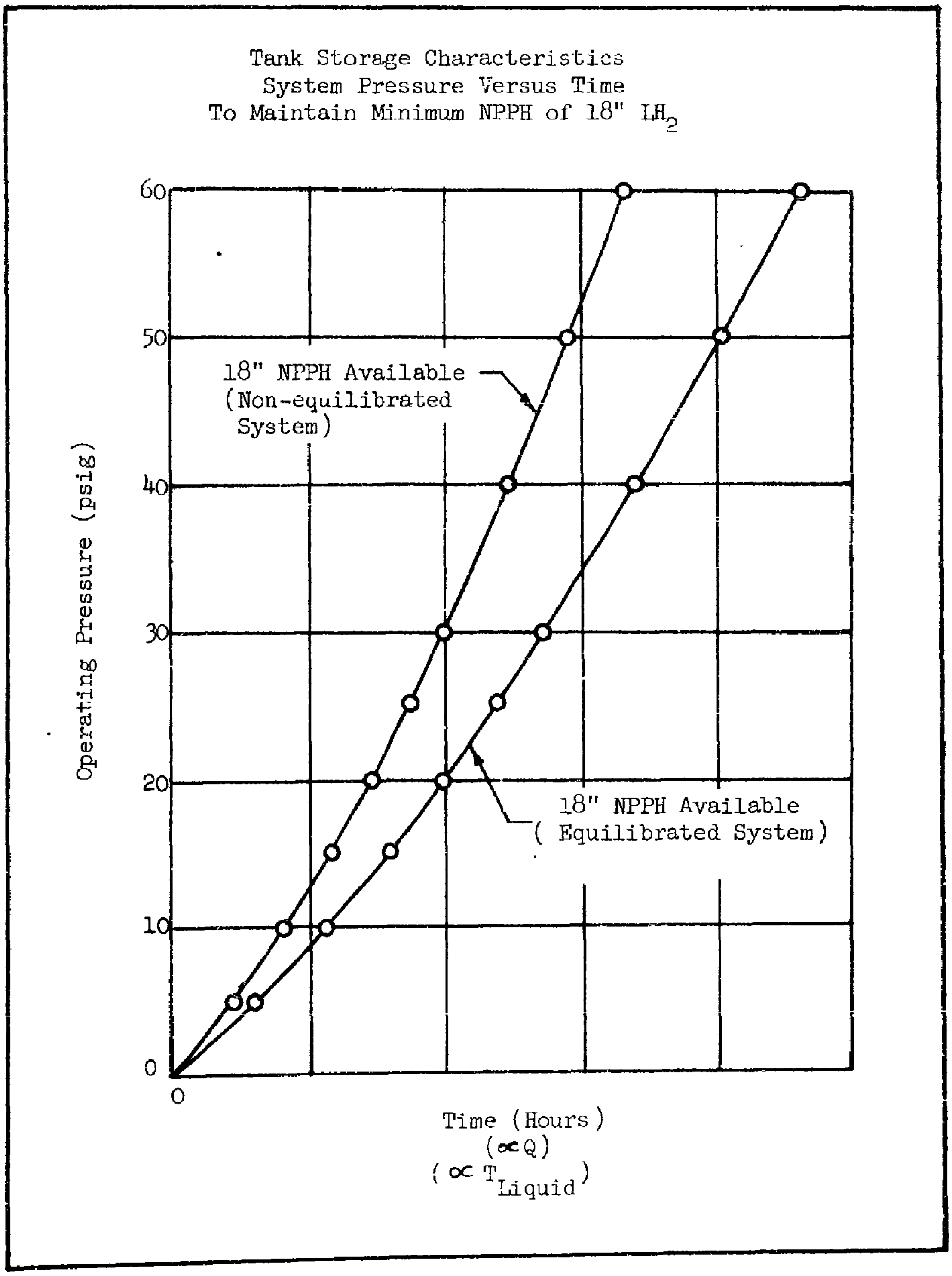


FIGURE 3.7
EXAMPLE OF PROPOSED PROTOTYPE TEST CURVES
WITH TANK FULL, HALF FULL, OR QUARTER FULL



4.0 MANUFACTURING PROCEDURE

4.1 Bladder Fabrication

The development of a bladder as the means of positively expelling fluids from a storage vessel required the greatest effort in the design and manufacture of the positive expulsion system. The bladder concept was selected after a broad survey of the existing methods of positive expulsion was completed and analyzed.

Beech Engineering Report No. 9501, "Development of Positive Expulsion Systems for Cryogenic Fluids, Phase I," describes in detail the literature and "state-of-the-art" survey. Various manufacturers are listed with comments regarding their interest and ability to fabricate a satisfactory bladder. Numerous materials are also listed with qualification tests conducted to prove out or eliminate specific materials.

The result of the surveys, research, and testing by Beech indicated that the most promising and satisfactory positive expulsion system would use a spherical bladder constructed of 3 separate 1/2 mil Mylar membranes free to act independently of each other. The details of fabrication of the bladder finally selected and tested are described in the following paragraphs. The G. T. Schjeldahl Company, Northfield, Minnesota, was the supplier of several preliminary test bladders and of the final bladders for the prototype positive expulsion units.

Beech drawing 7035-1007 is a specification control drawing covering the fabrication of the bladder. The bladder is constructed of 3 plys of 1/2 mil Mylar, type A electrical grade. Plys are unbonded except in the mount seal area and composed of 24 equal gores continuous from polar cap to mounting flange opening. All seams are butt-jointed and taped on both sides with Schjeldah GT 300 1/2 x 1/2 x 3/4 tape. Special instruction to the manufacturer requires that the air entrapped between all plys be kept below 4 cubic inches at room temperature and one atmosphere. The bladder mount was furnished by Beech to the bladder manufacturer and assembled to the bladder using Schjeldahl GT 200 liquid resin and GT 400 strip adhesive. Following the installation of the mount washer and nut, properly torqued, safety wire was attached to prevent loosening. The entire mount and bladder assembly was packaged and shipped to Beech for installation in the positive expulsion system. After inspection of the bladder and mount assembly, the bladder was lowered into the dewar and expanded against the inner shell. The helium bottle assembly, vacuum capsule, and system plumbing were then installed in preparation for bladder tests.

4.2 Inner and Outer Tank Shells

The dewar for the prototype positive expulsion units is spherical and has a capacity of approximately 27 gallons. The construction generally follows the 1000 gallon tank described in the report on Phase I of this program.

The outer shell is 6061-0 aluminum alloy .090 thick and the inner shell is type 302 stainless steel .090 inch thick. This size tank and material permitted the utilization of available hemispheres, thus saving lead time. The stainless steel hemispheres for the inner tank are 23.69 inches I.D. and the aluminum alloy hemispheres are 27.75 inches I.D.

The maximum design system operating pressure was 60 psig to allow adequate flexibility in tests.

The inner tank shell is welded to a neck mounting fitting which supports the tank inside the outer tank. The outer tank also has a neck mounting fitting which provides a base for both the vacuum capsule and the inner tank neck fitting. The inner and outer tank neck fittings are bolted together with an insulating spacer bushing between them to minimize heat losses between tanks. The inner tank neck fitting also serves as the support for the helium bottle flange and bladder mount. The outer tank neck fitting is aluminum and the inner tank fitting is 304 stainless steel.

4.3 Insulation Technique

The space between the inner and outer shell of the dewar is filled with an insulating powder such as Pearlite, Cab-O-Sil H5 or Santocel A2. When this volume is evacuated and filled with powder, an exceptionally efficient light-weight insulation is obtained. Long-term storage of liquid hydrogen requires the best insulation techniques available.

4.4 Summary of Problem Areas

The problems encountered during the fabrication and testing of the positive expulsion system and solutions are discussed in this section. Several problems which became apparent during the testing program were created by fabrication techniques and were easily corrected. Other problems occurred in areas such as seals in which trouble was not anticipated because of good experience in the past with a particular seal. Cryogenic seals require considerably more research and testing to produce a reliable, dependable method of creating a leak-tight joint between two mating surfaces. Such a seal should work under all applications of a similar nature and be practical for installation by shop personnel.

The major problems involved the bladder cell and the cold helium gas regulator. The regulator problem could be solved by a redesign of the present dome loader regulator. The bladder problem will require a program which is design to provide new bladder materials and fabrication techniques leading to a more serviceable bladder.

SUMMARY OF PROBLEM AREAS

PROBLEM	SOLUTION
(1)	(1)
Leakage of hydrogen gas from bladder to vacuum space through multiple seals located between the helium bottle flange, bladder mount, and the inner tank neck fitting. The seals performed satisfactorily during early testing but began leaking and becoming progressively worse as liquid hydrogen was used. The vacuum in the dewar and vacuum capsule deteriorated at an increasing rate beyond the ability of a vacuum pump to maintain a reasonable vacuum (ref. Figure 2.5).	The Naflex seals used in this system have previously performed satisfactorily under similar pressures and temperatures. Failure in this application is not clearly understood, but may have been caused by cleanliness, machining of surfaces, or installation procedures. At the present time the Naflex seal is still considered the best seal for this application.
(2)	(2)
Leaks in silver brazed connections in tubing and between helium bottle and internal hydrogen tube.	The substitutions of arc welding of all connections in place of silver brazing, provides more assurance of a leak-tight joint. Arc welding also eliminates the weakness of silver brazed joints to crack under thermal shock. In addition to arc welding the hydrogen tube into the helium bottle, an expansion loop was formed in the tube to permit additional thermal expansion (ref. Drawing 7035-1005).
(3)	(3)
APCO regulator No. 122900-X2 failed to function properly and prevented the bladder from being pressurized.	The regulator was returned to the manufacturer and repaired. It was found to have a broken roll pin which caused a poppet to be jammed. A new, larger diameter pin was installed.

PROBLEM	SOLUTION
(4)	(4)
The Mylar bladder was ruptured through all three membranes adjacent to the neck mounting flange. Another hole occurred in the outer membrane at the juncture of the polar cap and the gores. The failures were confirmed only after the bladder was removed and visibly inspected. Indication of possible bladder rupture was observed during testing after 15 to 20 partial and full expulsion cycles. The individual membranes may have ruptured at different times since indication of failure would be apparent only after all three had ruptured.	Failure of the bladder is expected after continuous expulsion cycles. The number of cycles before failure must be sufficient to provide reliability for practical use as a positive expulsion system. Test of one bladder of this same construction completed 79 cycles without failure. Although a sufficient number of bladders has not been tested to provide a statistically significant number of cycles to failure, it was expected that a bladder should far exceed 30 cycles. Improvements should be obtained by minimizing membrane lapping under mounting ring. During manufacture, the purging of the volume between the membranes with helium gas and then not permitting over 4 cubic inches of trapped gas to remain when sealing the bladder to the mounting ring, should remove the chance of frozen air particles from rupturing the membranes.
(5)	(5)
A second Mylar bladder failed after two cycles of liquid hydrogen expulsion. A six-inch gash and a four-inch rupture were noted in the inner and middle ply of Mylar adjacent to the mounting flange. A third failure existed near the polar cap and affected the outer ply only. Reference Figure 3.5.	Same as Item (4)
(6)	(6)
The two-stage APCO regulator No. 122900-X2 failed to provide a regulated flow of 200 $\pm$ 20 psi to the 0-60 psi expulsion gas regulator. A continuous flow of helium was passed out the first stage vent port.	Diaphragm controlling first stage regulator was split. Diaphragm was replaced by valve manufacturer.

SUMMARY OF PROBLEM AREAS (Continued)

PROBLEM	SOLUTION
(7)	(7)
The third Mylar bladder failed after 1-1/2 cycles of liquid hydrogen expulsion in the same manner described in Item (5). Not more than a 2 psi differential was imposed on the bladder during the test runs.	Tests indicate that present bladder construction does not have the reliability required to expel liquid hydrogen. The present bladder material and construction must be improved to provide satisfactory service. Additional study and testing should be conducted to determine the material and construction methods required to supply serviceable bladder cells for LH_2.
(8)	(8)
The two-stage APCO regulator No. 122900-X2 failed to provide a 0-60 psi expulsion pressure to the unit	Poppet in second stage was jammed. Regulator returned for repair. Differential expansion of dissimilar metals at cryogenic temperatures tends to cause the unit to become inoperable.
(9)	(9)
The vent line fitting at bottom of regulator No. 122900-X2 was cracked during disassembly of the unit.	Regulator returned to manufacturer for repair.

5.0 CONCLUSIONS AND RECOMMENDATIONS

1. Additional research and testing should be conducted which will lead to bladders capable of considerably more cycles than the present tests have shown possible. Reliability studies using the best bladder materials and construction should yield data necessary for determining the future of such expulsion methods. Preliminary tests conducted during Phase I on a 1/2 mil Mylar 3 membrane bladder showed the feasibility of this type of positive expulsion system; however, during Phase II, one bladder failed after 20 cycles, a second bladder failed after 2 cycles, and a third bladder failed after 1-1/2 cycles. Many more types and sizes of bladders should be tested to failure to provide significant statistics relative to the reliability of bladders for space applications. Specific tests should be conducted to determine the operational limits within which the bladder can safely perform. A test to determine the maximum pressure differential allowable across the bladder should contribute a factor of safety for bladder expulsion cycles. Figure 5.1 illustrates a possible improvement toward increased bladder protection.

2. When a bladder has been selected as meeting the requirements of a reliable positive expulsion system, then additional prototype testing should be performed to determine the practical size limitations of this type of system.

3. Insulation for long-term storage dewars is extemely important. The use of mul iple layer super insulation should be investigated to reduce the heat leak rate to a minimum and still maintain a flightweight article.

4. The prototype positive expulsion units designed for this testing program required complex interrelationship of regulators to provide control for the varied test conditions. The development of a single regulator to perform the required functions would simplify and increase the reliability of an expulsion system and would be possible when designed for a specific mission in an operational vehicle.

5. The weight of the positive expulsion system can be reduced considerably by substituting lightweight materials and flightweight components. The removal of certain valves and gauges from the unit and installed in the ground equipment and the elimination of the net positive pressure head system will permit a lighter, more compact unit for use in an operational vehicle.

6. The necessity of the equilibration fan in the tank to circulate the hydrogen and prevent thermal stratification should be determined. Although theoretically it is necessary to incorporate a fan or similar device, the actual value has not been proven during testing. The increase in performance may not warrant the addition of the fan; but, on the other hand, it may be an absolute necessity in order to have successful storage and expulsion.

7. Investigation should be made into the possible changes in physical characteristics that may take place in the bladder material as a result of the fabrication and liquid hydrogen testing of the bladders. There appears to be some visual evidence that the Mylar bladder material is somewhat more brittle and less tear resistant after being fabricated into the bladder. Since it was not feasible to make any actual tear test of the material in the completely fabricated bladder, but only on the bladder material which had failed after being submerged in the liquid hydrogen, it cannot be said with assurance whether the fabrication or low temperature service might have changed the physical characteristics of the material. No scientific comparison was attempted between new Mylar fabric, Mylar fabric in a completed bladder, and the fabric in a bladder which had been tested in liquid hydrogen. The possibility that the fabrication process, low temperature environment, general aging, or a combination of these factors might change the physical characteristics should be considered.

8. The premise made in Phase I of this contract stated that substantial cyclic life might be anticipated for any bladder successfully withstanding the initial ten (10) cycles. The unsatisfactory life of several bladders during this last phase of the program would indicate the necessity of having a full reliability program with sufficient numbers of bladders and cycles to produce a reliability number, mean-time-to failure rate for the selected bladder.

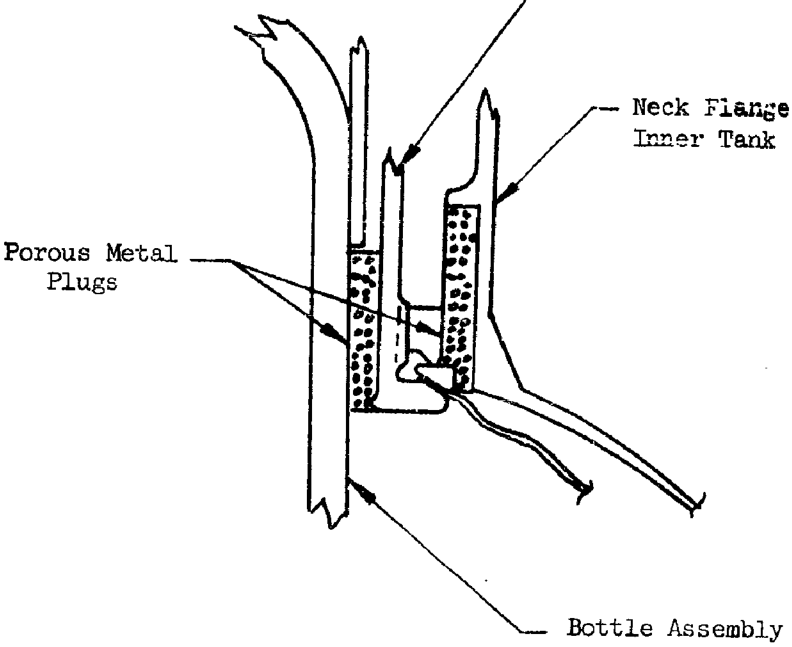
9. Although Phase I report concluded that there was no significant difference in the expulsion of fluid whether the expulsion was inward or outward, some consideration might be given to the effect of each method on the failure of the bladder material. Since most of the Phase I expulsion tests were in the outward direction and results were favorable, while all Phase II tests were in the inward expulsion direction and several failures occurred, additional testing would be desirable to disprove any relationship between expulsion direction and bladder failure.

Although considerable difficulty has been experienced during the test program on two particular problems, solutions doe not seem unsurmountable. The regulation problem is a development problem which can be solved. It cannot be solved, however, installed in the present system which requires the satisfactory operation of the bladder unless the bladder becomes reliable first. On the other hand the bladder reliability cannot be determined unless a regulator which functions satisfactorily is installed. This situation requires the separation of the problems and the solving of at least one before results can be obtained.

The possibility of early bladder failures in Phase II testing could not be anticipated since the Phase I tests indicated quite successful results could be expected. The desirability of correlating the difference in results of Phase I and Phase II test with regard to the bladder failures is not possible without repeating some of the Phase I tests.

Phase I proved the feasibility of bladder expulsion of liquid hydrogen and Phase II has shown that a positive expulsion unit can be fabricated which will store liquid hydrogen in a bladder within a dewar. Expulsion has been demonstrated with the completed system although continuous and reliable operation has not been achieved. Data required, to prove the feasibility of long term expulsion, was not obtainable since the Net Positive Pressure Head (NPPH) figures could not be recorded during the short or interrupted test runs.

FIGURE 5.1
BLADDER PROTECTION THROUGH USE OF
POROUS METAL PLUGS



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expulsion system. The test program describes the data acquired and test setups used to determine the heat transfer rate to the fluid and the operational characteristics of the system. A summary of problem areas encountered during the fabrication of the unit has been included. Solutions to the problems presented by the prototype units are discussed and recommendations for future expulsion units are summarized.

(Ref.) Phase I, Beech Engineering Report No. 9501
AFFTC TR 60-70 December 1960

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